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*Dr*

## REGENERATIVE FUEL CELL SYSTEM

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TECHNICAL REPORT AFAPL-TR-70-53

AUGUST 1970

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## REGENERATIVE FUEL CELL SYSTEM

W. A. Titterington

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## FOREWORD

This report summarizes the work performed in the design and evaluation of a Regenerative Fuel Cell System by the Direct Energy Conversion Business Section, General Electric Company, Lynn, Massachusetts. It is part of the requirements of Air Force Contract F33615-69-C-1140, Project 3145. Administration of the work is under the direction of the Air Force Aero Propulsion Laboratory (APIP-1), Wright-Patterson Air Force Base, Ohio. Mr. D. R. Warnock is the task engineer, and Capt. B. J. Durante is the project engineer for the Laboratory.

This technical report is submitted in accordance with Data Item B004 of the Contract. It covers the work accomplished during December 1968 to June 1970. This report was submitted in June 1970.

Publication of this report does not constitute Air Force approval of the report's findings or conclusions. It is published only for the exchange and stimulation of ideas.

D. R. Warnock  
Electrochemical Energy Conversion  
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Aerospace Power Division

## ABSTRACT

The objective of this Contract was to develop and define the performance and life characteristics of regenerative fuel cell technology for space applications. This report describes the system, analyses, component configurations, test results and conclusions derived from this work effort for this initial developmental program phase. Laboratory-type evaluation electrolysis single-cells (3 x 3 inch size) were fabricated and operated on performance and life tests to determine the design parameters in unit design. Full-size fuel cell units were assembled and tested, with the final 8-cell stack completing 975 hours of testing at the design current density (100 ASF) and 180°F cell temperature. An electrolysis stack configuration was designed and several single and 3-cell stacks were performance tested to develop the design concept. A complete 150 - 200 watt breadboard regenerative fuel cell system was designed and fabricated. The system was performance tested to demonstrate the system energy efficiency (approximately 33%), which compared favorably with a predicted energy efficiency of 38%. Two daily mission cycles (12 minutes and 16.5 minutes fuel cell discharge durations) were completed in the regenerative system prior to an electrolysis unit failure. This testing demonstrated the technical feasibility of an integrated regenerative system approach. Additional hardware development is required to demonstrate system reliability and successful completion of a 45 day eclipse season mission test.

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## 1.0

### INTRODUCTION

The purpose of this work effort was to design and develop a 150 - 200 watt breadboard regenerative fuel cell system based on an integrated system design concept. The General Electric Company solid polymer electrolyte (SPE) can be utilized in a regenerative fuel cell system for communication satellite applications in two distinct and different system approaches:

- a) An integrated system using a primary fuel cell unit to provide electrical power during the eclipse period operated from separate gas storage tanks, and a separate electrolysis unit to regenerate the reactant gases from the fuel cell product water.
- b) A unitized system in which the system consists of a number of individually packaged cells which can operate in either the fuel cell or electrolysis mode, with each cell consuming or regenerating its own reactant gases depending on whether it is in the fuel cell or electrolysis mode.

The primary consideration in the selection of an integrated system approach is the component design flexibility which permits optimization of the fuel cell unit and electrolysis unit for the most favorable operating condition and design configuration for the specific mission duty cycle. For example, in the General Electric Company solid polymer electrolyte system concept, the membrane cross-diffusion of the reactant gases increases with cell temperature and exposed active cell area for a given membrane or cell thickness. Considering this effect in the integrated system approach it is therefore desirable to select the operating temperature of each unit for maximum system efficiency and minimize cell area and time on the reactant gases to reduce gas diffusion losses. The unitized system approach would have to compromise on designed operating temperature in either the fuel cell or electrolysis mode due to gas diffusion influences with a common cell area and cell thickness.

The "Statement of Work" for this Contract is attached as Appendix I to define the performance and mission objectives of the regenerative fuel cell system and the Contract requirements. In addition to the breadboard system work effort, a second fuel cell stack was required to be fabricated and life tested in the program to demonstrate performance and life capability at the selected regenerative system operating conditions.

The typical daily mission operating time for the fuel cell and electrolysis units in an integrated system approach is illustrated in Figure 1 where the peak daily operating time for the fuel cell is 72 minutes on the 23rd day with the corresponding 22 hours of electrolysis operation required to regenerate the gas reactants. For daily cyclic operation of both components for the 45 day eclipse season and the subsequent

shutdown for the 135 day dormant period, this mission is repeated for a total of 10 times over the design life objective of 5 years resulting in approximately 370 hours of operation for the fuel cell and 7000 hours for the electrolysis unit.

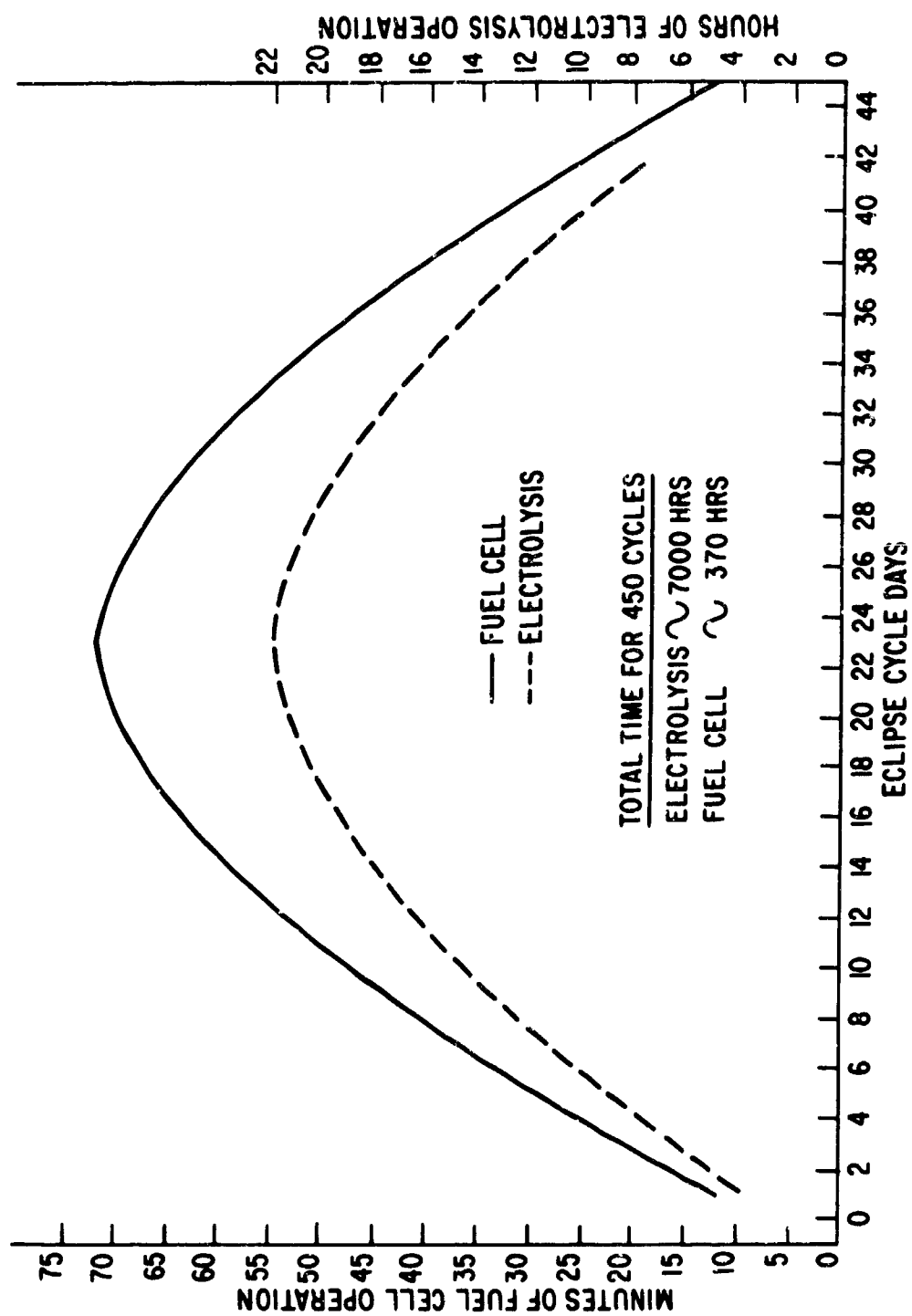


Figure 1. Electrolysis and Fuel Cell Comparative Operating Times -  
Time of Operation for Each Day of Mission -  
Component Time vs. Daily Mission Time

INTEGRATED REGENERATIVE FUEL CELL SYSTEM DESCRIPTION

Figure 2 is a fluid flow schematic of the basic flight system concept. The basic components of the system are: 1) a fuel cell stack for electrical power generation; 2) an electrolysis unit to replenish the hydrogen and oxygen gas consumed by the fuel cell; 3) a hydrogen storage tank; 4) an oxygen storage tank; 5) a deionizer/water accumulator to provide water contaminant control and water storage; and 6), the associated fluid controls (regulators, valves, piping, etc.) to control the system reactants.

Due to the high power requirements of the system and the operating time of the electrolysis unit, the fuel cell stack single cell active area resulted in being relatively large (.375 ft<sup>2</sup>) compared to the electrolysis unit (.038 ft<sup>2</sup>) at the selected current density/life capability of each component. The smaller active cell area of the electrolysis unit was selected to minimize the gas diffusion losses across the membrane since the unit is exposed to the reactant gases throughout the complete daily mission. This, in effect, increases overall system energy efficiency. The fuel cell is isolated from the gas reactant tanks during that portion of the daily mission when the unit is not required to provide electrical power by the indicated gas tank shut-off solenoid valves. This limits gas diffusion losses across the fuel cell unit to limit the effect on the system energy efficiency. In addition, the free gas volumes within the fuel cell unit were sized small to minimize the gas trapped downstream of the solenoid valves which will ultimately diffuse across each cell of the unit until pressure stabilization is obtained by consumption of the smallest size gas volume which, in this unit, is the hydrogen side.

The electrolysis stack power is derived from the solar panel array and its operating time is a function of the gas consumed from the gas storage tanks by the fuel cell stack based on the daily mission discharge cycle as defined in Figure Nr. 1 of Exhibit "A" in Appendix I. The fuel cell stack consumes hydrogen and oxygen from the storage tanks to produce electrical energy and product water. As illustrated in Figure 2, the fuel cell product water is stored in a combination accumulator and deionizer bed during fuel cell operation. This water is "bulk" transferred to the oxygen side of the electrolysis stack by opening and closing the water solenoid valve on a timed basis. Heat generated by both the fuel cell stack and electrolysis unit is thermally conducted through the component containers to the satellite structure. This integrated regenerative system, therefore, operates in a closed cycle where the only interface intelligence between the satellite and the regenerative fuel cell system is electrical power either into or out of the system.

Figure 3 basically depicts the component parts of the fuel cell and electrolysis unit across a single cell assembly with the corresponding chemical reaction occurring at each cell electrode. Each cell within the fuel cell stack is connected electrically in series by externally connecting the associated electrode screens. Each cell within the electrolysis unit is series connected within the stack by means of

bipolar stacking of the single cells. Water transport within each unit is maintained by a wicking system to overcome the effects of the zero "g" environment in the application. In the electrolysis unit, the wicks also serve the function of maintaining electrical contact pressure against each cell electrode with the indicated electrical conductor providing electrical continuity to each coolant plate through the spring effect of the compressed wick.

The basic fuel cell operation is conventional. Hydrogen and oxygen react at the anode and cathode, respectively, with hydrogen ions ( $H^+$ ) released to the solid polymer electrolyte and migrating to the cathode side to combine with oxygen to produce water while the electrons ( $e^-$ ) travel in the external load circuit.

The electrolysis operation is somewhat unique in the solid polymer electrolyte concept for this system. At the start of an electrolysis cycle, the system product water is contained on the oxygen side of the cell. This is a result of the previous fuel cell cycle operation. The system is initially charged with water to provide water for startup and to saturate the system. When electrolysis operation is initiated, an electro-osmotic water flux which is a function of ion exchange capacity, water content of the membrane, temperature and current density, is established. The electro-osmotic flux is several times the quantity of water consumed by electrolysis. This water is transported protonically from the oxygen side of the cell to the hydrogen side. The water supply on the oxygen side becomes deficient as the water is accumulated on the hydrogen side, and a water gradient is established. Osmosis of water from the hydrogen side to the oxygen side then takes over to keep the oxygen evolution electrode supplied with water. At equilibrium, the osmotic water transport equals the electro-osmotic water transport. This is the mechanism which sustains water flow to the oxygen side and allows electrolysis operation without further addition of water from the fuel cell side, thus the water shut-off solenoid valve can be closed after the bulk water transfer.

The  $H_2O/H_2$  and  $H_2O/O_2$  separators illustrated in Figure 2 within the electrolysis stack minimize the amount of water transferred to the gas storage tanks during electrolysis. The amount of excess water initially added to the system above that required for a 72 minute fuel cell run is designed to overcome system water losses to the components during the calendar life of the application.

The hydrogen and oxygen regulating valves control the hydrogen and oxygen back-pressures to approximately 165 psia on the electrolysis unit during the electrolysis mode, thus minimizing the amount of water carried over into the storage tanks. The  $H_2$  and  $O_2$  electrolysis regulating valves are referenced to the vacuum of the space environment and are thus absolute pressure regulators.

Figure 4 illustrates the various functions and operating modes of the system and components during a typical 24-hour period of the 45 day eclipse season. Starting at time zero with the assumption that the electrolysis unit is in the electrolysis

mode, the oxygen and hydrogen tank pressures are increasing due to generation of gases by the unit. At the same time, a back-pressure is maintained on the hydrogen and oxygen sides of the electrolysis unit by the  $H_2$  and  $O_2$  electrolysis regulating valves (approximately 165 psia). A two-way  $H_2$  tank pressure switch removes the solar array power from the electrolysis unit and closes a resistive load type circuit on the unit to operate the electrolyzer (Step (1) in Figure 4) as a fuel cell when the hydrogen tank pressure reaches approximately 160 psia. This fuel cell mode causes a decay in the hydrogen and oxygen side pressure of the electrolysis unit due to gas consumption. The hydrogen and oxygen storage tanks are prevented from decaying in pressure by the electrolysis unit check valves indicated in Figure 4. Pressure decay continues on the electrolysis unit until a pressure level of approximately 5 psia is reached, at which point the oxygen-side electrolysis unit pressure switch opens and removes the resistive load circuit from the unit and places the electrolyzer on open circuit (Step (2) in Figure 4).

As indicated in Figure 4, the fuel cell stack is at zero electrical potential due to the fuel cell stack inlet gas solenoid valves being closed. Since the oxygen side volume of the fuel cell stack is approximately 10 - 20 times larger than the hydrogen side, oxygen will continue to diffuse across the ion exchange membranes after the solenoid valves are closed, resulting in hydrogen consumption by diffusion on the electrode. The magnitude of the equilibrium oxygen pressure on the fuel cell during the 135-day dormant period and the standby conditions between daily "eclipse season" load applications will depend on the relationship of the respective fuel cell stack hydrogen and oxygen volumes back to the gas solenoid valves. Prior to fuel cell load application, therefore, the unit must be activated such that the oxygen is removed from the hydrogen side and so that the gas solenoid valves are opened (Step (3) in Figure 4). This is most efficiently removed by charging the fuel cell stack electrically. During the electrical charging period the fuel cells will operate initially as oxygen concentrator cells and then as electrolysis cells until hydrogen is restored to the hydrogen side.

Removal of power to the fuel cell is on a timed basis, followed by the opening of the fuel cell stack gas solenoid valves (Step (4)) in Figure 4. The fuel cell will thus be in a fully activated condition at open circuit prior to load application.

Application of the fuel cell stack load (Step (5)) results in the closing of the hydrogen tank pressure switch due to gas consumption but no operation of the electrolysis stack since the electrolysis unit oxygen-side pressure switch is still open. Removal of the fuel cell stack load (Step (6)), closing of the fuel cell solenoid valves and opening of the water solenoid valve results in a "bulk" transfer of the generated fuel cell product water in the accumulator to the oxygen side of the electrolysis unit. This results in an increase in pressure on the oxygen side of the electrolysis unit, thus closing the contacts of the oxygen-side pressure switch (Step (7)). Solar array power is thus applied to the electrolysis unit resulting in the generation of hydrogen and oxygen.



The water solenoid valve is closed on a timed basis (Step (8)) to prevent overpressurization of the fuel cell product water system. This is determined on the final system by proper selection of oxygen gas volumes as a result of the satellite installation or breadboard piping requirements and the dead band spread in opening and closing of the electrolysis unit oxygen side pressure switch.

After the electrical load is removed from the fuel cell stack and subsequent closure of the gas solenoid valves, the residual gases would continue to decrease in pressure until final oxygen-side takeover resulting in a zero electrical potential once again on the fuel cell stack.

The fuel cell is designed to operate nominally at 150°F temperature and gas reactant pressures of approximately 50 psia, which results in an average cell performance of .80 volt at 100 amps per square foot current density. The selected operating condition was based on previous fuel cell life history consistent with the requirements of the regenerative system application for high fuel cell performance to obtain a high system energy efficiency. Selection of the electrolysis unit operating condition was influenced greatly by the gas tank storage pressures from a system trade-off study conducted in the program.

System reliability is obtained by adding redundant components. It is estimated that a minimum system energy density of 20 watt-hr/lb can be realized over a power range of 1 to 5 KW for an approximate system reliability of .95.

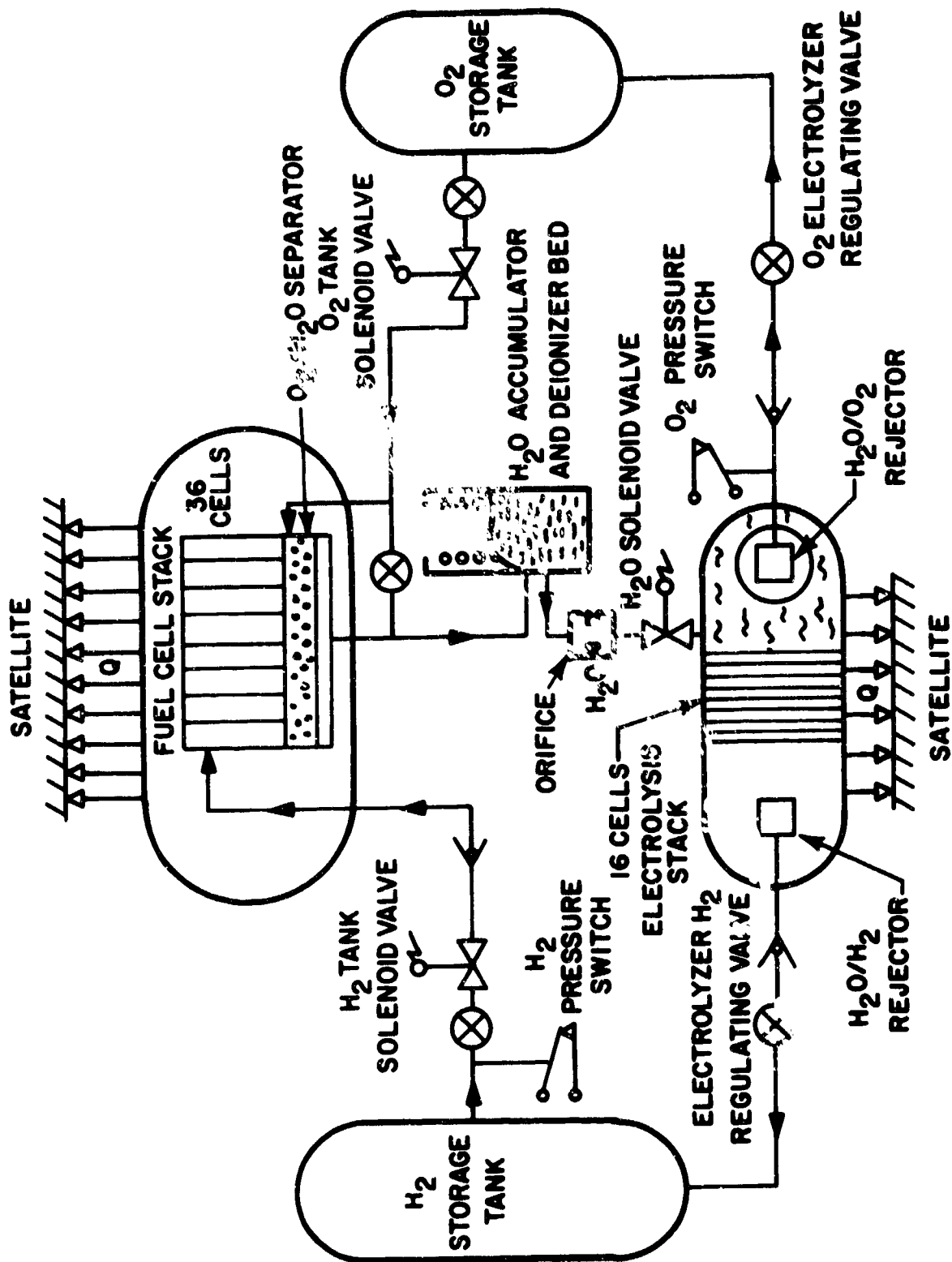
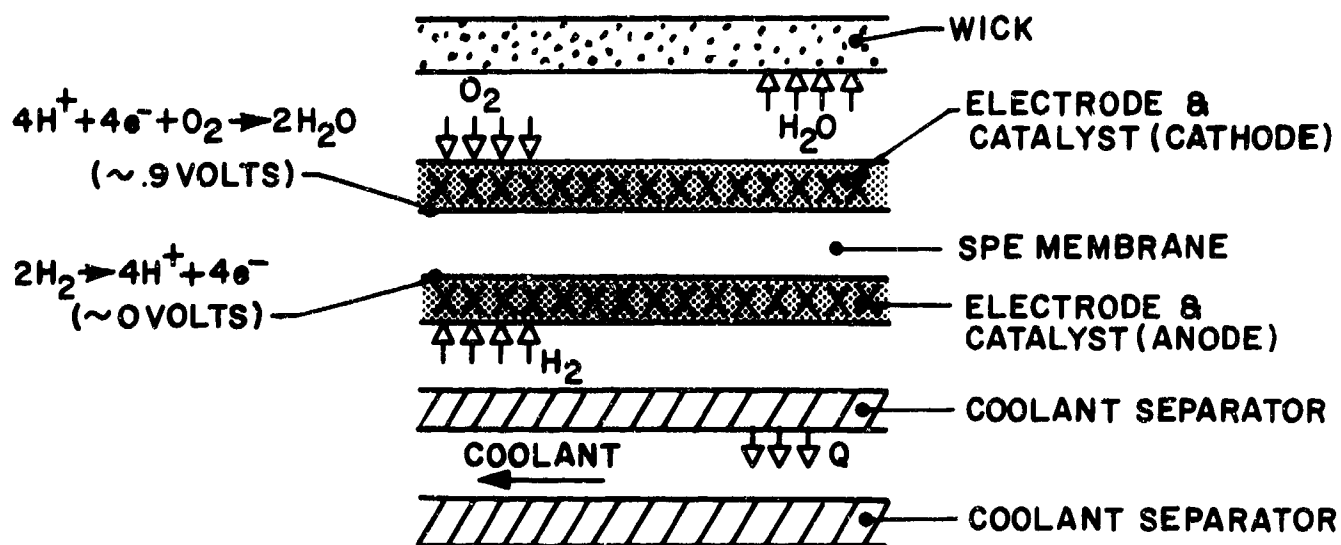


Figure 2. Basic Integrated Regenerative Fuel Cell System Fluid Flow Schematic (1.2 KWH System)

## SECTION OF FUEL CELL OPERATION



## SECTION OF ELECTROLYSIS OPERATION

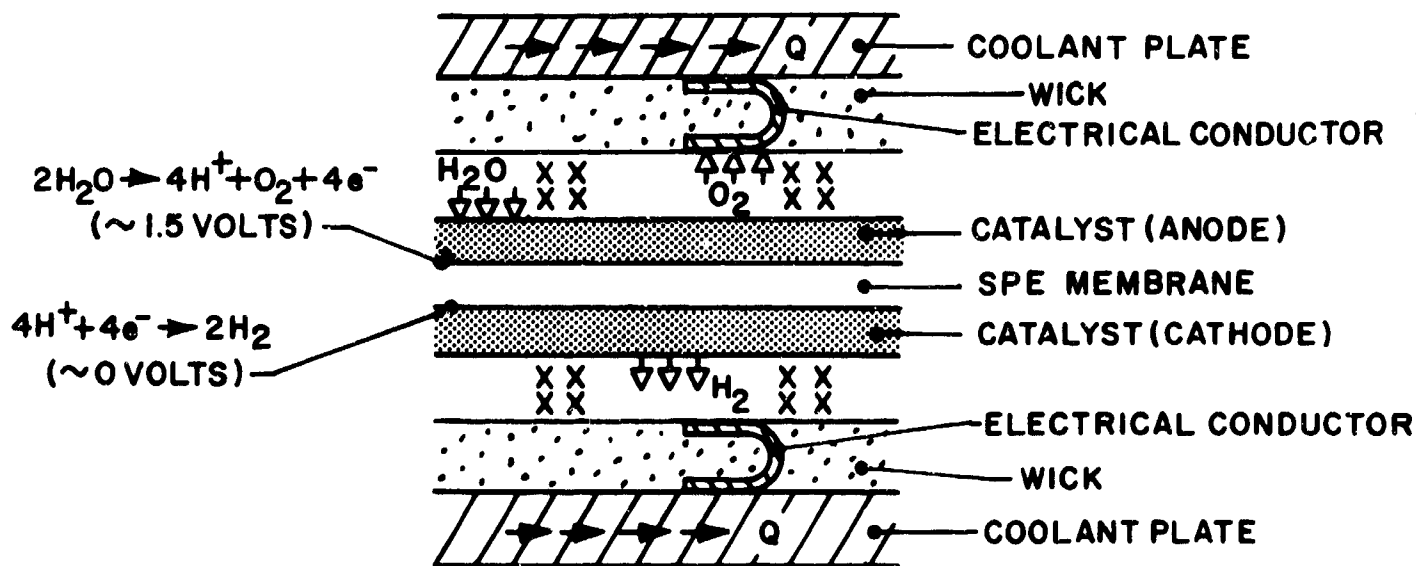
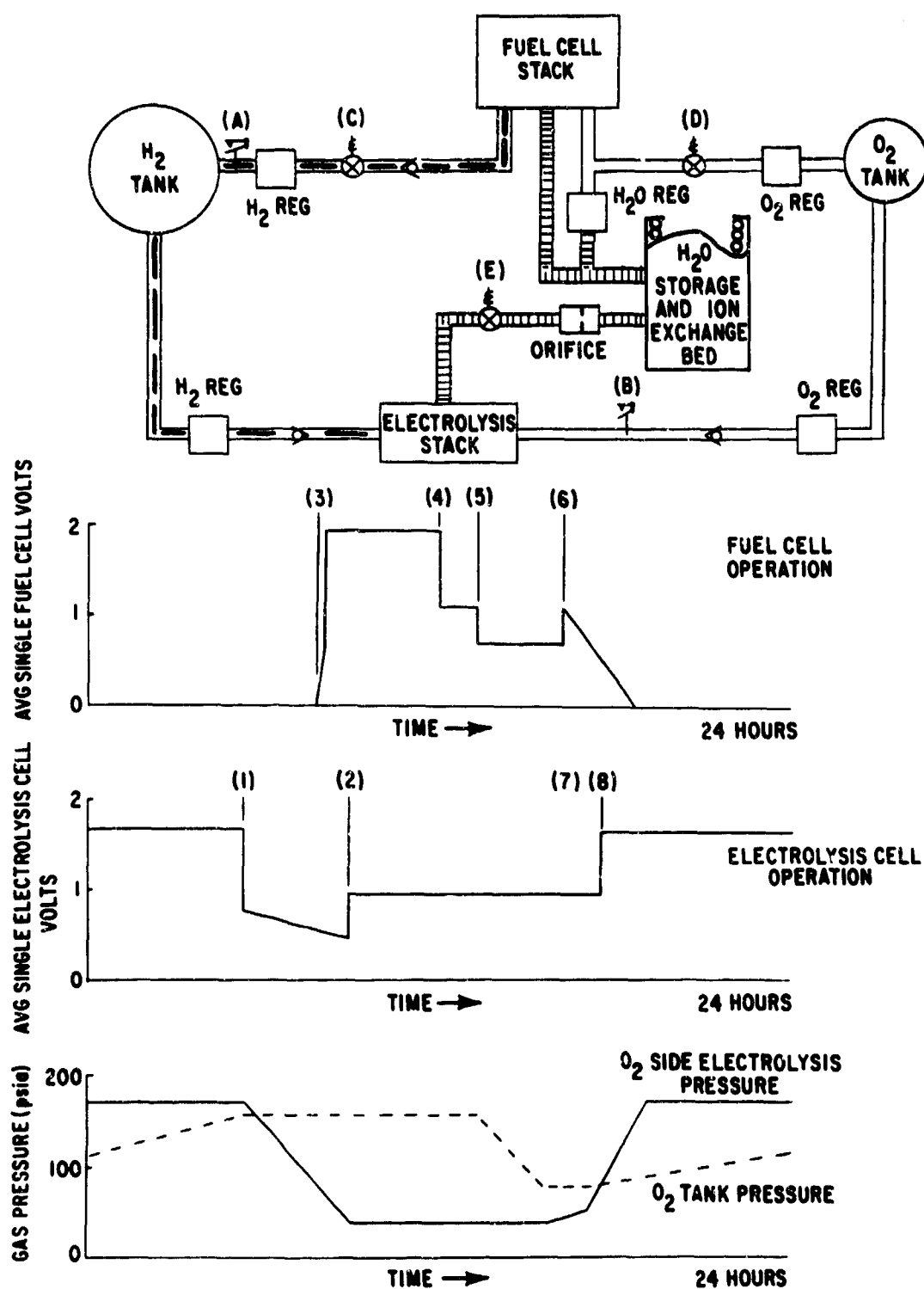


Figure 3. Sections of Fuel Cell and Electrolysis Operations



- Step (1) Pressure Switch (A) opens to shut off power to electrolysis unit and close circuit for electrolysis unit fuel cell mode.
- (2) Pressure Switch (B) opens load circuit on electrolysis unit from fuel cell mode.
- (3) Satellite electronic control applies power to fuel cell stack to initiate fuel cell activation.
- (4) Satellite electronic control removes power from fuel cell stack and opens valves (C) and (D).
- (5) Satellite electronic control applies fuel cell stack load. Pressure Switch (A) closes during fuel cell consumption.
- (6) Satellite electronic control removes fuel cell stack load, closes (C) and (D) and opens (E).
- (7) Pressure Switch (B) closes during water transfer.
- (8) Satellite electronic control closes valve (E).

Figure 4. Integrated Regenerative Fuel Cell Basic Functional Diagram

### 3.0 SUMMARY OF WORK EFFORT

#### 3.1 Laboratory Work

During this program the GE/DECBS Fuel Cell Laboratory supported the electrolysis unit design effort by testing numerous laboratory single cells in a 3 x 3 inch active area standard cell fixture as modified for the particular area of evaluation. A number of these units were assembled and tested with IR and D funding. This laboratory testing was conducted to investigate the following major design areas:

a) Performance and life capability of the basic solid polymer electrolyte (SPE) in the flooded anode mode (Cell TMS-342).

b) Performance and life capability of the membrane and electrode assembly in the wicked cathode mode of operation (Cell TMS-423).

c) Performance and life capability of an improved catalyst structure in the wicked cathode mode of operation (Cell TMS-480).

d) Effect of wick thickness and type on performance and life (Cells TMS-410 and 417).

e) Effect of mission cycling on performance and life (Cell TMS-417 and 423).

f) Evaluation of fuel cell operation with the electrolysis unit in a wicked configuration (Cell TMS-456).

g) Effect of high-pressure operations with wicks (Cell TMS-414).

Figures 5, 6 and 7 illustrate the life capability of the membrane and electrode structure in the electrolysis mode of three cells assigned for life evaluation. The majority of cell operation was at the design current density of 128 ASF to evaluate the cell performance against the maximum allowable voltage of 1.8 at the end of life (7000 hours). All three cells successfully demonstrated this performance capability.

The following major design parameters in the electrolysis unit design were established by the work effort of the GE/DECBS Fuel Cell Laboratory in the program:

a) Selection of a General Electric proprietary electrode structure to obtain improved electrolysis performance.

b) Establishment of a .012 inch gas gap on each side of the cell to obtain good fuel cell performance, while still maintaining a wicked electrolysis configuration.

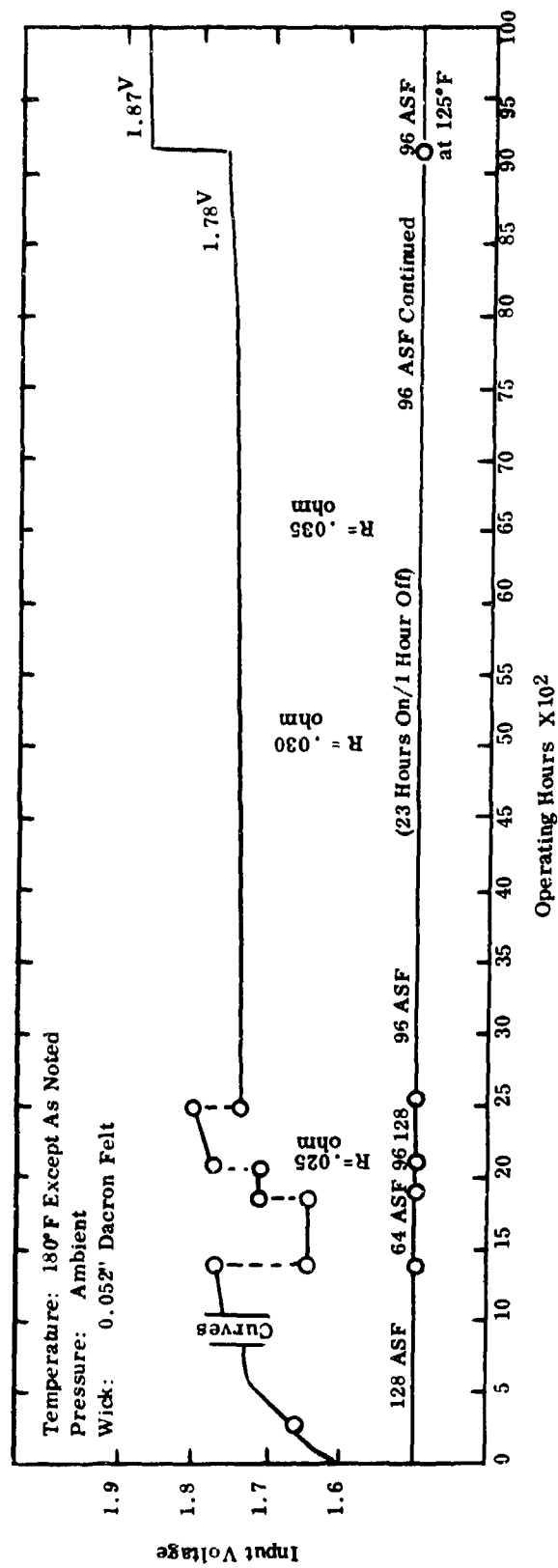


Figure 5. Wicked Cathode Electrolysis Capability vs. Life - TMS-423 (Pt-5% Ir)

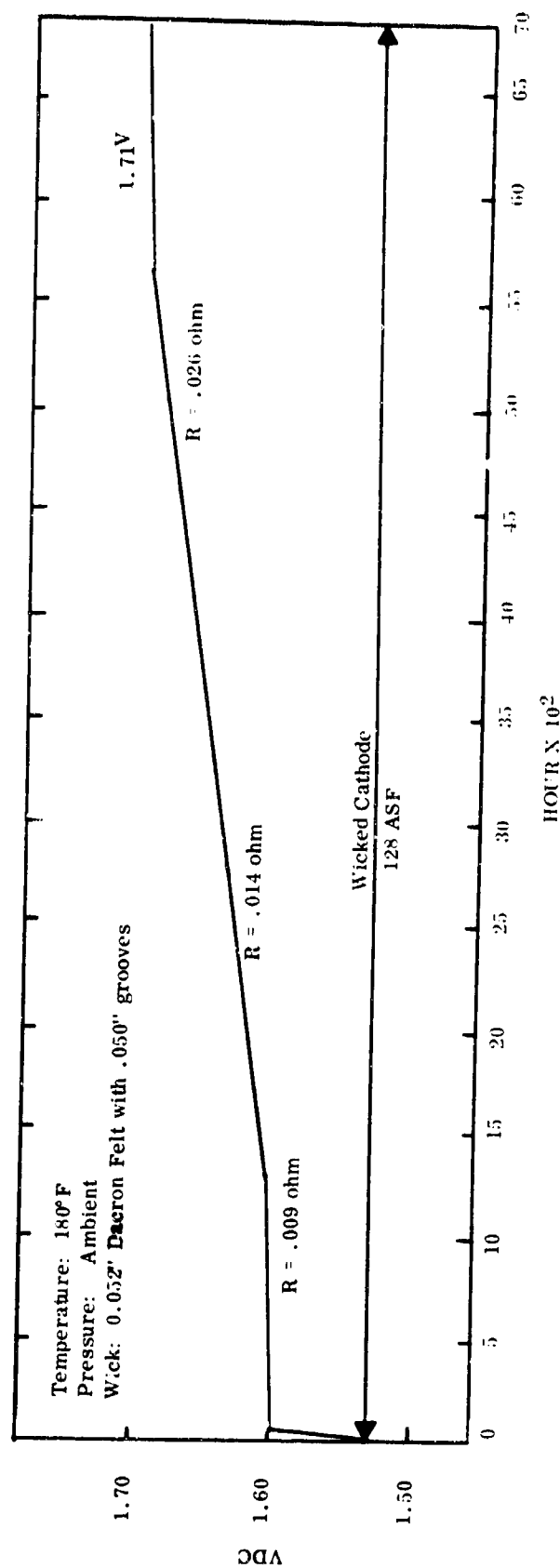


Figure 6. Life Endurance Profile of General Electric Proprietary Catalyst in the Wicked Cathode Mode - TMS-480

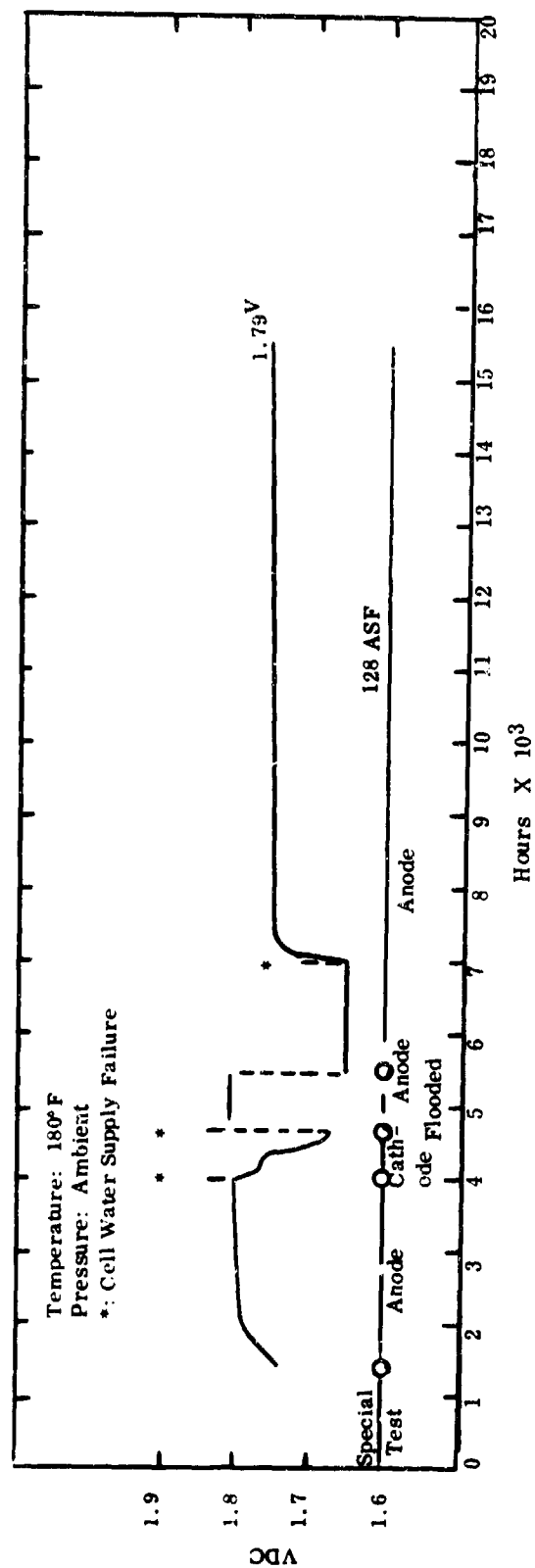


Figure 7. Life History of TMS - 342 (Pt-5% Ir) -- "R" Membrane Capability



c) Selection of the Dacron felt wick as the basic wick structure material against the cell electrode.

d) Establishment of performance penalties for various operating conditions to support the system trade-off analysis (gas pressure, cell temperature, anode and cathode water feed).

e) Selection of platinized niobium screening to reduce cell electrical contact resistance in the bipolar stacking configuration.

f) Establishment of a cell drying procedure by electrolysis operation to condition the cell for acceptable performance in the fuel cell mode.

### 3.2 System Trade-off Analysis

During the program, time-sharing computer programs called ELSYS\*7 and 12 were developed to conduct various system trade-off studies. These programs made it feasible to perform accurate and systematic parametric studies of the integrated regenerative fuel cell system with sophisticated analytical methods. The analysis concentrated on optimizing the electrolysis unit operating conditions and effects of various cell configurations to obtain the specification objective system energy efficiency. The primary fuel cell unit had been basically designed from a previous development effort (Contract 33615-67-C-1830), thus its operating conditions were already established within the design capability of the configuration. The fuel cell stack size was fixed at 35 cells with an active area of 54 sq in. per cell and an operating temperature at 180°F which subsequently was lowered to 150°F to increase reliability. The fuel cell operating gas pressures were also held constant at approximately 50 psia.

The following electrolysis unit design and operating parameters were investigated:

- a) Cell active area: 5.53 and 8.0 sq in.
- b) Cell operating temperature: 120, 150 and 180°F
- c) Gas generating pressure range: 80 to 1000 psia.
- d) Electrolyzer cell oxygen side catalyst:
  - . Pt - 5% Ir.
  - . GE/DECBS improved catalyst.
- e) A humidity of 100% in the vicinity of the hydrogen electrode.

Figures 8 and 9 show the variation of the system energy efficiency for electrolyzer cell active areas of 5.53 and 8 sq in., respectively. The variation in energy efficiency is shown in Figures 9 and 10 as a function of maximum reactant gas storage pressure for various operating temperatures and the two types of oxygen electrode catalysts. The larger cell area results in lower cell current density as shown in Figures 10 and 11 for the same conditions as shown in Figures 8 and 9, respectively. The larger cell area results in a lower cell voltage which increases the energy efficiency but this also results in a lower Faradaic efficiency which decreases the energy efficiency. Both the Faradaic efficiency and voltage of the electrolyzer cell are affected by both operating temperature and pressure. The delicate balance gives the result that, in general, the energy efficiency increases with increase in electrolyzer operating temperature at low operating pressures. The energy efficiency conversely increases, in general, with a decrease in the operating temperature at the higher operating pressures.

The energy efficiency decreases with an increase in operating pressure due to the effect of pressure on the Faradaic efficiency. It is desirable, however, to operate at the highest operating pressure possible commensurate with an acceptable value for the system energy efficiency in order to minimize the size of the reactant storage tanks.

An electrolyzer cell with an 8 sq in. area gives approximately the same energy efficiency as the 5.53 sq in. cell area due to the low cell voltage that results from the lower current density. The larger cell size produces a somewhat heavier electrolyzer unit but the electrolyzer volume would not substantially change since the volume is principally a function of the amount of water to be electrolyzed. Laboratory tests have indicated less performance loss with time at current densities of less than 100 ASF as compared with a current density of 128 ASF. Laboratory tests also indicated that the electrolyzer life is adequate for this application operating at 128 ASF.

Although it may be desirable to consider larger electrolyzer cell sizes in future designs for longer life with possibly some sacrifice in system weight, the 5.53 sq in. cell is predicted to give a system energy performance greater than 0.45 if the design uses the improved oxygen electrode catalyst and the cell is operated at the optimum temperature. An operating temperature of 120°F was selected for the electrolysis unit as a result of this study with a maximum operating gas reactant pressure level of 166 psia.

The effect of the primary fuel cell conditions during unit standby was also investigated during the program. Since the fuel cell unit contained a large number of cells with a large exposed area to the reactant gases, any membrane gas diffusion during the non-operating mode will reduce the system energy efficiency below the desired 45%. Table I illustrates the effects of fuel cell standby conditions on the system energy efficiency under various standby conditions (unit temperature, gas pressure,

trickle load or open circuit) with a fixed electrolysis unit operation. The loss of 7% system energy efficiency (Case 1 to Case 3) should be noted from this table if the fuel cell unit is not isolated from the gas reactant storage tanks during the standby condition.

Table 1  
Effect of Fuel Cell Standby Condition on  
System Energy Efficiency

<u>Case</u>	<u>Cell Temperature During Standby, °F</u>	<u>H<sub>2</sub> Cell Pressure During Standby, psia</u>	<u>Equiv Diffusion Current Density, ASF</u>	<u>Fuel Cell Current Density, ASF</u>	<u>System Efficiency, %</u>
1	150	~50	0*	0	45.75
2	75	14.7	.546	0	40.75
3	75	51.7	.846	0	38.12
4	150	14.7	1.494	0	34.16
5	150	51.7	1.621	0	33.43
6	75	51.7	.846	.26	36.5

\*Fuel Cell isolated during standby.

Note: Electrolysis unit temperature maintained at 120°F and oxygen fuel cell pressure maintained at 52.3 psia

Illustrated in Appendix II of this report is a sample of the type and number of design data points investigated for one particular case in the system trade-off study effort. This particular investigation showed a predicted 38.4% system energy efficiency for the breadboard regenerative fuel cell system if the primary fuel cell stack is not isolated from the gas storage tanks during the standby condition.

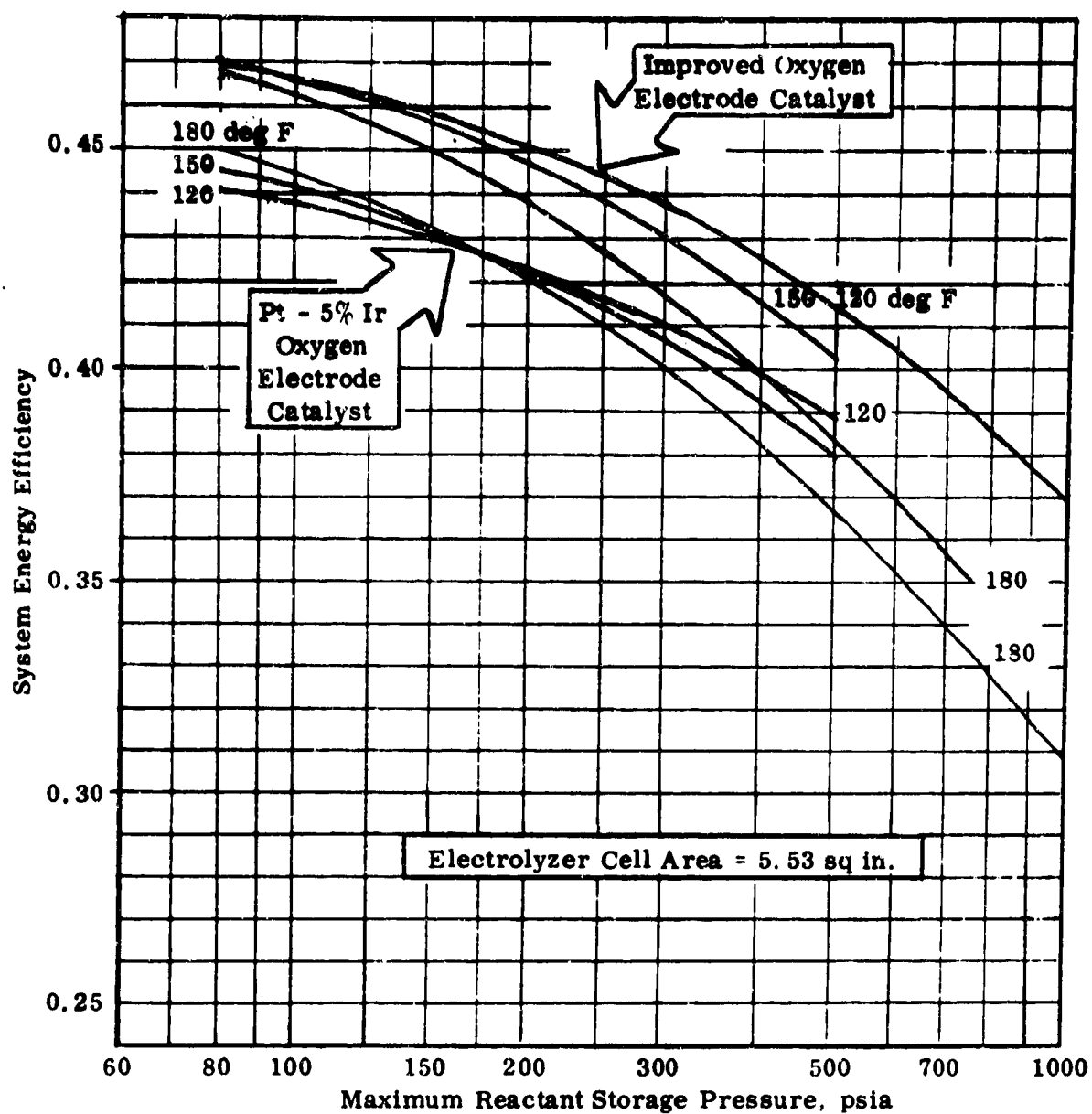


Figure 8. The Variation in the Energy Efficiency of a Regenerative Fuel Cell System with Reactant Gas Storage Pressure for Constant Electrolyzer Operating Temperatures and Two Types of Oxygen Electrode Catalysts (Results from the ELSYS\*7 Program) - Electrolyzer Cell Area = 5.53 sq in.

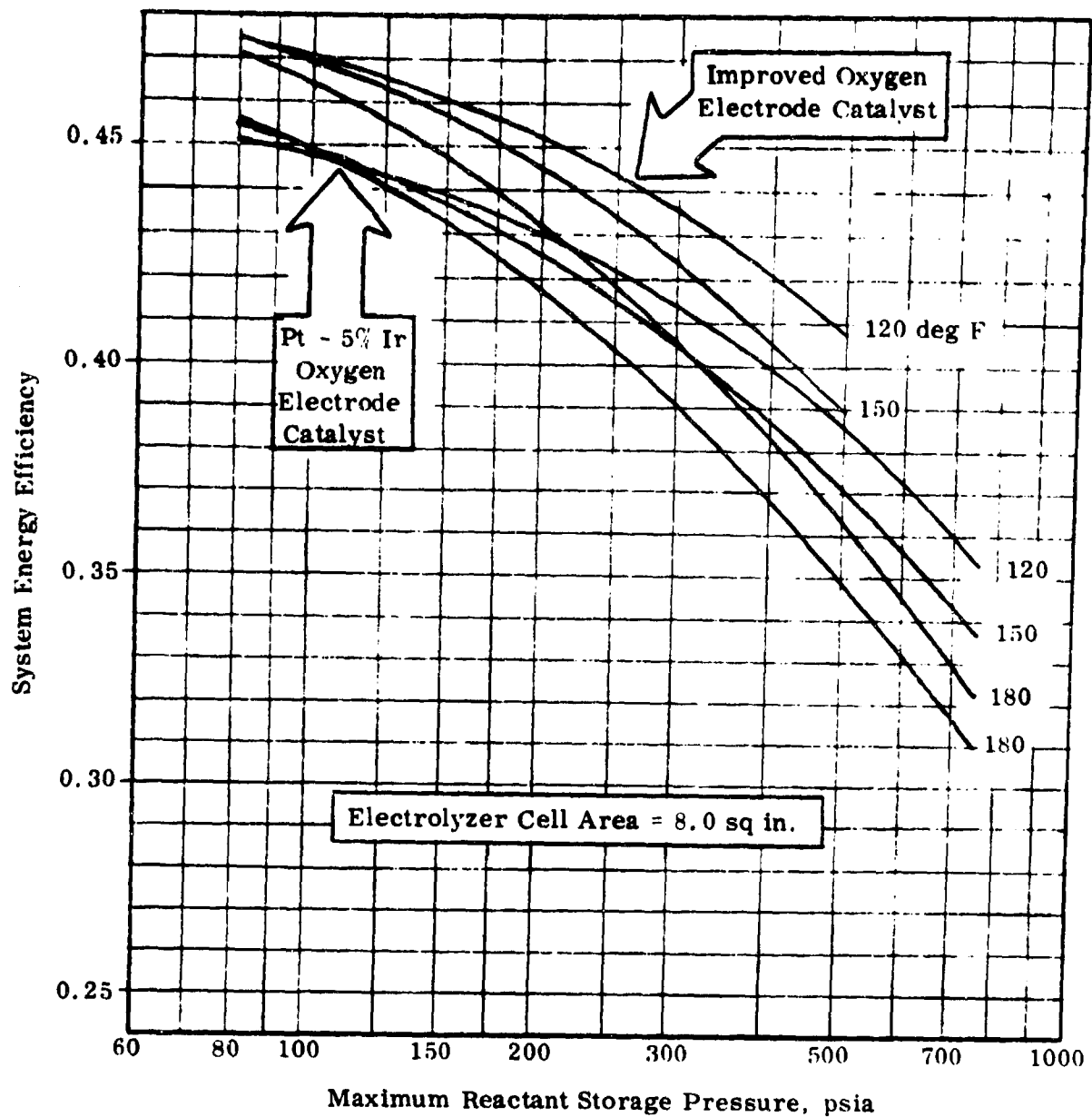
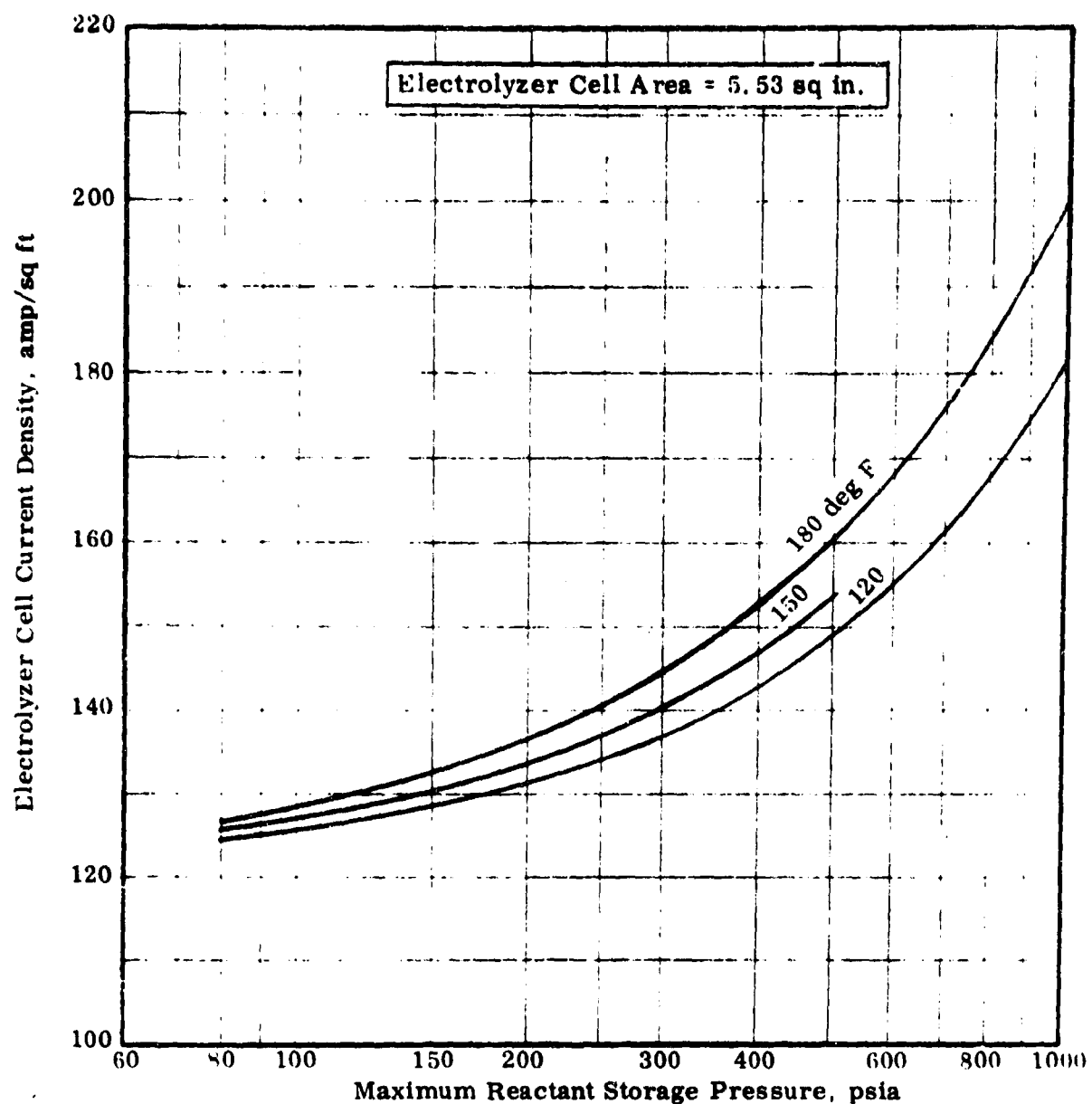
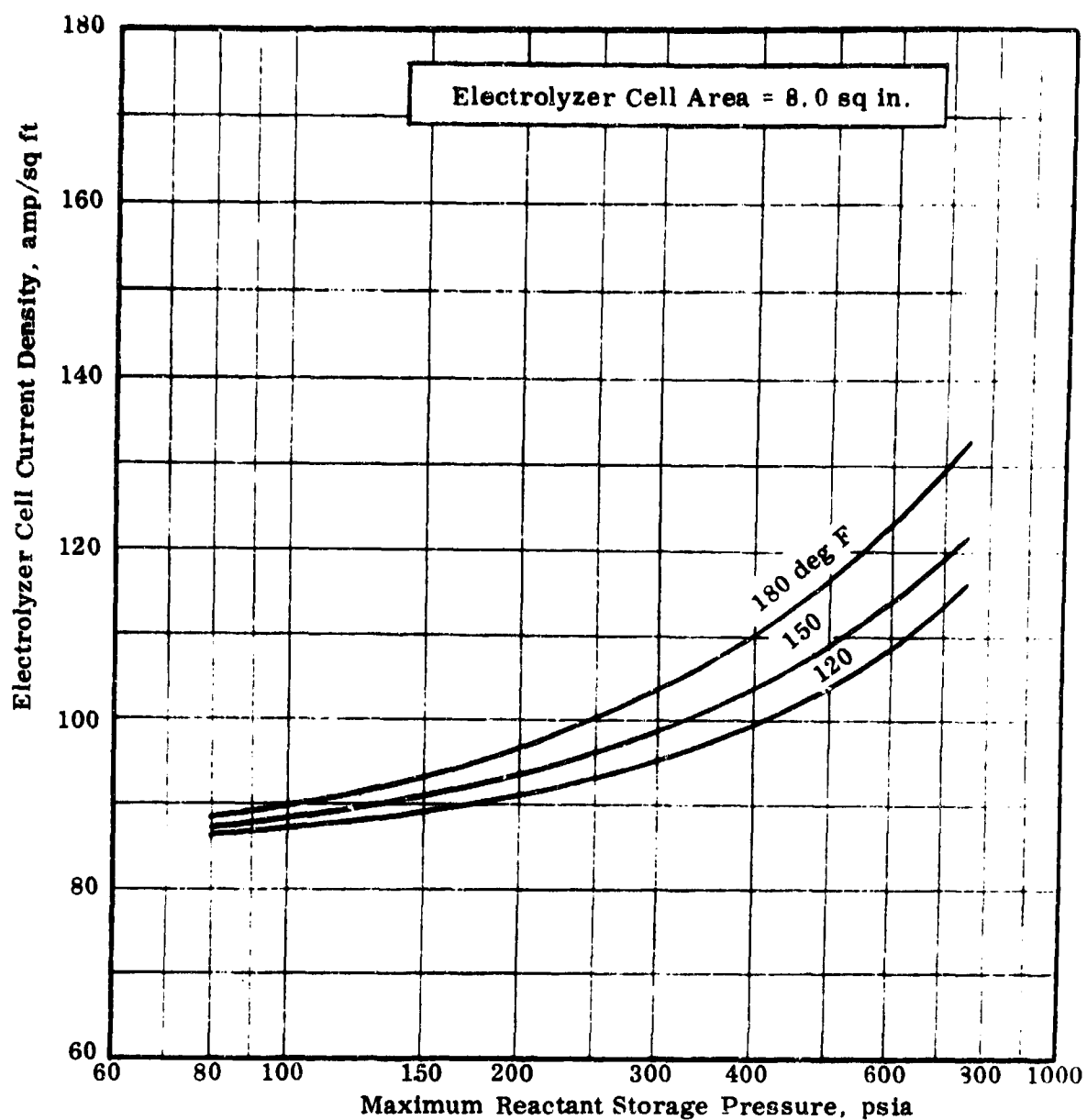


Figure 9. The Variation in the Energy Efficiency of a Regenerative Fuel Cell System with Reactant Gas Storage Pressure for Constant Electrolyzer Operating Temperatures and Two Types of Oxygen Electrode Catalysts (Results from the ELSYS\*7 Program) - Electrolyzer Cell Area = 8 sq in.



**Figure 10. The Variation of Electrolyzer Cell Current Density with Reactant Gas Storage Pressure for Various Constant Electrolyzer Cell Operating Temperatures (Results are Independent of the Catalyst System and are from the ELSYS\*7 Program.) - Electrolyzer Cell Area = 5.53 sq in.**



**Figure 11. The Variation of Electrolyzer Cell Current Density with Reactant Gas Storage Pressure for Various Constant Electrolyzer Cell Operating Temperatures (Results are Independent of the Catalyst System and are from the ELSYS\*7 Program.) - Electrolyzer Cell Area = 8 sq in.**

### 3.3 Component Design

#### 3.3.1 Fuel Cell Stack Design

The fuel cell unit selected for the regenerative breadboard system was based on an improved version of a back-to-back cell configuration previously developed for the Air Force under Contract F33615-67-C-1830 and further developed on General Electric Company IR and D funding. Development effort under this contract was directed towards a demonstration life test of 1000 hours with design modifications as recommended from the initial evaluation of the cell design concept and discussed in the final program report (Technical Report AFAPL-TR-69-43) of Air Force Contract F33615-67-C-1830. Further modifications were also incorporated as a result of the General Electric funded IR and D effort. Following is a list of these modifications and design changes generated by this contract in the fuel cell unit utilized in the regenerative fuel cell system:

- a) Increased cell perimeter bonding widths and the utilization of the high-temperature AF-42 tape.
- b) Revised current collection screen and bar configuration to eliminate possible gas leakage paths.
- c) Improved oxygen-side flow distribution by addition of a labyrinth flow path and cell perimeter gasketing.
- d) Substitution of Teflon for Vexar in the oxygen cavities to prevent material deterioration.
- e) Improved hydrogen-side labyrinth flow utilizing polysulfone strip embedment in the hydrogen-side screens.
- f) Improved oxygen humidification by passing the inlet gas through the product water wicking.
- g) A fuel cell checkout test ("pedigree cell test") prior to completion of the module buildup.
- h) Addition of a Teflon insulating labyrinth screen in the coolant cartridge assembly.
- i) Improved 17-7 pH corrosion resistant springs for end plate loading.
- j) Utilization of a spring-loaded test case design which provides safe pressure relief in the event of a cell failure.



k) Substitution of titanium end frames to eliminate internal gas manifold leakage.

l) Addition of an oxygen inlet and outlet tube Mylar baffle to prevent membrane puncture by the gas tube in the oxygen side gasket.

m) Relocation of the hydrogen inlet at the bottom of the unit to introduce the hydrogen into the module at the wettest portion of the membrane.

n) Substitution of improved edge current collection configuration between modules to isolate the end frame deflection from the current collection tie rods.

o) Addition of a catalytic burner in the unit hydrogen inlet tube to the module to reduce possibility of oxygen inerts from burning on the cell surface.

p) 100% visual inspection of the electrode gold screens to eliminate possibility of membrane puncture by broken screen strands.

Figure 12 shows the stack configuration of an 8-cell fuel cell unit. Figure 13 illustrates the conceptual design for a flight prototype unit which substitutes a heat pipe cartridge for the liquid coolant cartridge utilized in this program. It is basically comprised of a number of adhesive bonded modules containing two cells each having a common hydrogen gas compartment. Each 2-cell module is separated by an oxygen frame/screen gasket assembly, thus providing a common oxygen gas compartment between the two adjacent modules. The entire assembly is held together by spring-loaded tie rods anchored to the anode and cathode end frame. A separate anode and cathode side end plate is spring-loaded from the end frame to compress and maintain the spacing of the gas cavity compartments independent of the oxygen gasket load force requirements. A cell edge current collection technique is utilized in the assembly which does not depend on the end frame tie rods for electrical contact loading between modules. Each cell and electrical bus bar is imbedded within the electrode catalyst and contains an integral gold current collection bar and tab on either side of the cell active area. These tabs are interconnected in the appropriate series connections external to the bonded cell perimeter and joined to load lead wires bolted to the anode and cathode end plate as shown in Figure 12.

Product water collection is obtained by individual Dacron woven sheets facing the oxygen side of each cell with a gas gap being maintained by a Teflon screen. This screen contains a molded labyrinth configuration as illustrated in Figure 13 to provide adequate distribution of the oxygen flow across the cell surface. The hydrogen side of the cell also contains a Ti-Pd metal expanded screen consisting of two .0035 inch thickness layers to provide the hydrogen-side gas gap. Both hydrogen and oxygen are manifolded through the oxygen gasket frame perimeter and the heat pipe cartridge. The oxygen flow is humidified by passing through the wicks between the stack edge and

the water separator prior to entering the oxygen manifold inlet on the stack end frames. The stack contains both inlet and outlet porting to provide purging capability for ground checkout type testing on bottle gas due to gas purity. The design operating point is at 100 ASF and 150°F cell temperature with an end-of-life voltage within the required  $28 \pm 10\%$  stack voltage. A total of six cells or three modules is capable of producing the breadboard regenerative system power requirement of 150 to 200 watts.

### 3.3.2 Electrolysis Unit Design

The electrolysis unit design developed in this program is shown in Figure 14, 15 and 16. Figure 17 illustrates the flight prototype configuration for a 14-cell stack. The basic stack consists of a number of single circular cells assembled between honeycomb end plates and contained within a pressure vessel. Cell gas sealing is accomplished by an O-ring type configuration as illustrated in Figure 16. The oxygen generated by each cell flows down the center of the stack to the water/gas compartment on the anode side. Hydrogen generated by each cell flows to the outer periphery of the cell and axially along the inside diameter of the pressure vessel to the water/gas compartment on the cathode side. The large diameter O-ring thus seals the oxygen side of the cell from the hydrogen and, conversely, the small diameter O-ring prevents hydrogen from entering the oxygen flow path down the center of the stack. The oxygen pressure vessel compartment is separated from the hydrogen compartment by the larger diameter end plate located at the bolted container flange interface as shown in Figure 15.

Each membrane and electrode assembly (M and E) is supported by two layers of Dacron felt wicks which are precompressed to 200 psi prior to stack assembly. These wicks, therefore, besides acting as the means of water transfer to the cell act as springs against each side of the cell when they are assembled in the stack. This concept permits the cell to be subjected to high differential gas pressures (approximately 200 psi) without damage to the ion exchange membrane.

Each cell is electrically connected in series in the stack by connecting the layer of screens on each side of the cell to the metal coolant plate through the welded tabs illustrated in Figure 16. These tabs pass through slots in the felt wick material and are an integral part of the current collection ring which is welded to a 4-layer screen assembly. This screen assembly forms a gas gap against the electrode surface and is approximately .012 inch in depth.

Heat generated by the cell is conducted through the water saturated felt wick material to a titanium coolant plate illustrated in Figure 16. The outer periphery of the plate is lipped and, through a layer of wick material, is pressed against the inside diameter of the pressure vessel which acts as a heat sink.

A water rejector is located in each gas compartment at the entrance to the hydrogen and oxygen outlet tubes. These rejectors consist essentially of two layers of porous Teflon (approximately .002 inch thick) bonded to a supporting plastic structure. Gas generated by the unit passes through the porous material while the water required for electrolysis is restrained by the small pore sizes of the Teflon film. The electrolysis unit design was continually modified throughout the program to improve performance and reliability. Following is a list of design modifications made to the original design concept during the program as a result of the development testing described in Section 4.0:

a) Substitution of a square O-ring configuration to prevent internal gas leakage during pressure reversals in the unit.

b) Substitution of an improved catalyst electrode structure to improve performance.

c) Addition of a platinization coating to the niobium screening to reduce electrical contact resistance.

d) Substitution of Dacron woven wick material (utilized in the main fuel cell stack) for the felt wicks in transporting the water to the individual felt cell wicks.

e) Reduction in the size of the oxygen delivery tube in the oxygen side water transport path and substitution of woven wicking to increase the water transport capability on the oxygen side.

f) Reduction in the size of the hydrogen and oxygen volumes to reduce the electrolysis unit fuel cell operating mode time and increase system efficiency.

g) Reduction in the length of the cell cooling fin flanges to eliminate clamping on the hydrogen side cell wick entrance.

h) Substitution of tantalum for stainless steel in the stack tie rod and nuts to eliminate iron contamination of the wicks and possibly the cells.

i) Substitution of "free" Mylar screen edge binders for the pressed polysulfone configuration to prevent screen edge puncture of the membrane.

j) Redesign of the bipolar current collection tab and ring in the cell assembly to improve current distribution.

The design operating point of the electrolysis cell is at 128 ASF, 120° F cell temperature, with an end-of-life single cell voltage limit of 1.8 volts. A total of three cells is capable of producing the gas required for the 150-200 watt breadboard regenerative system.

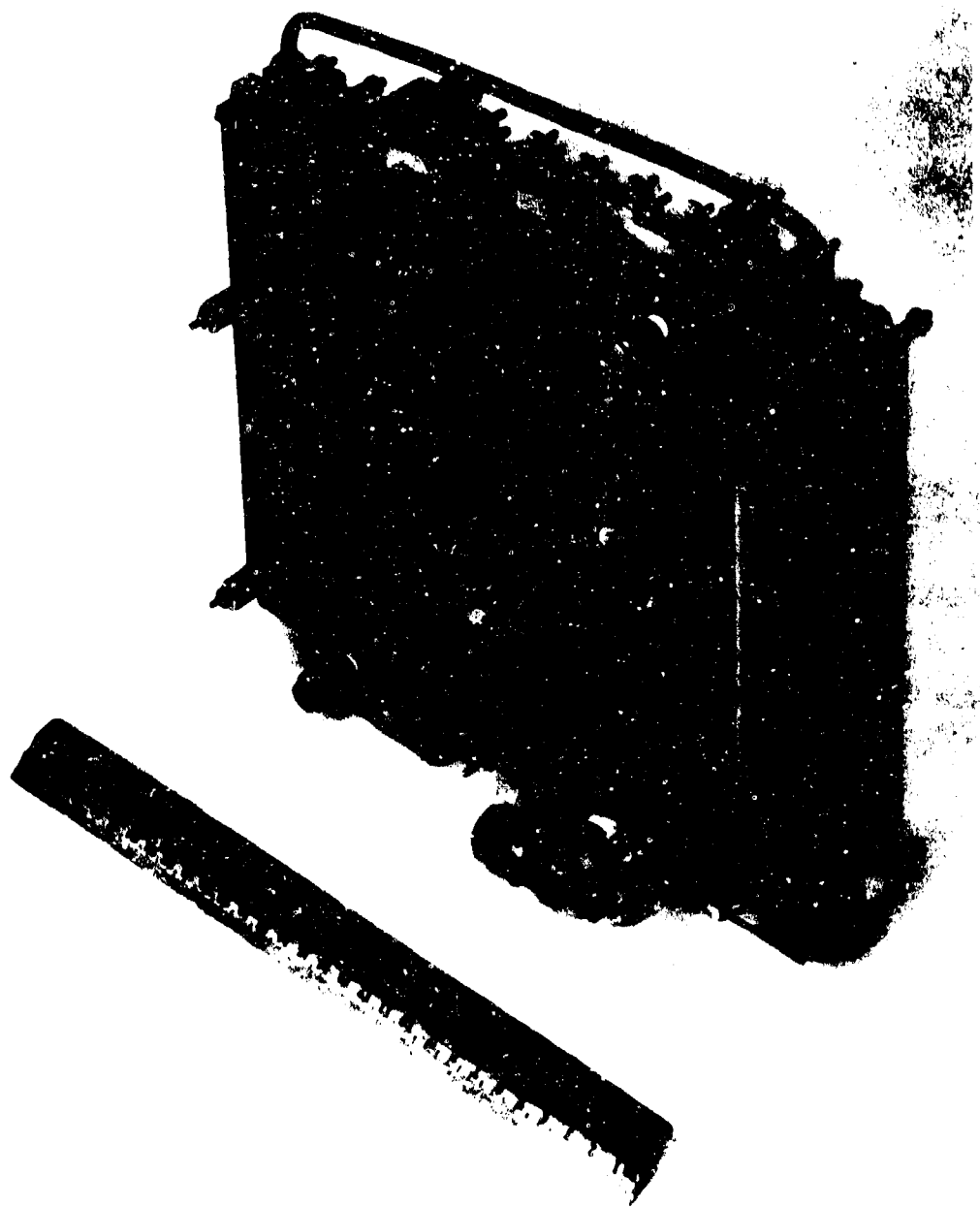


Figure 12. Fuel Cell Stack for 150-200 Watt Breadboard System

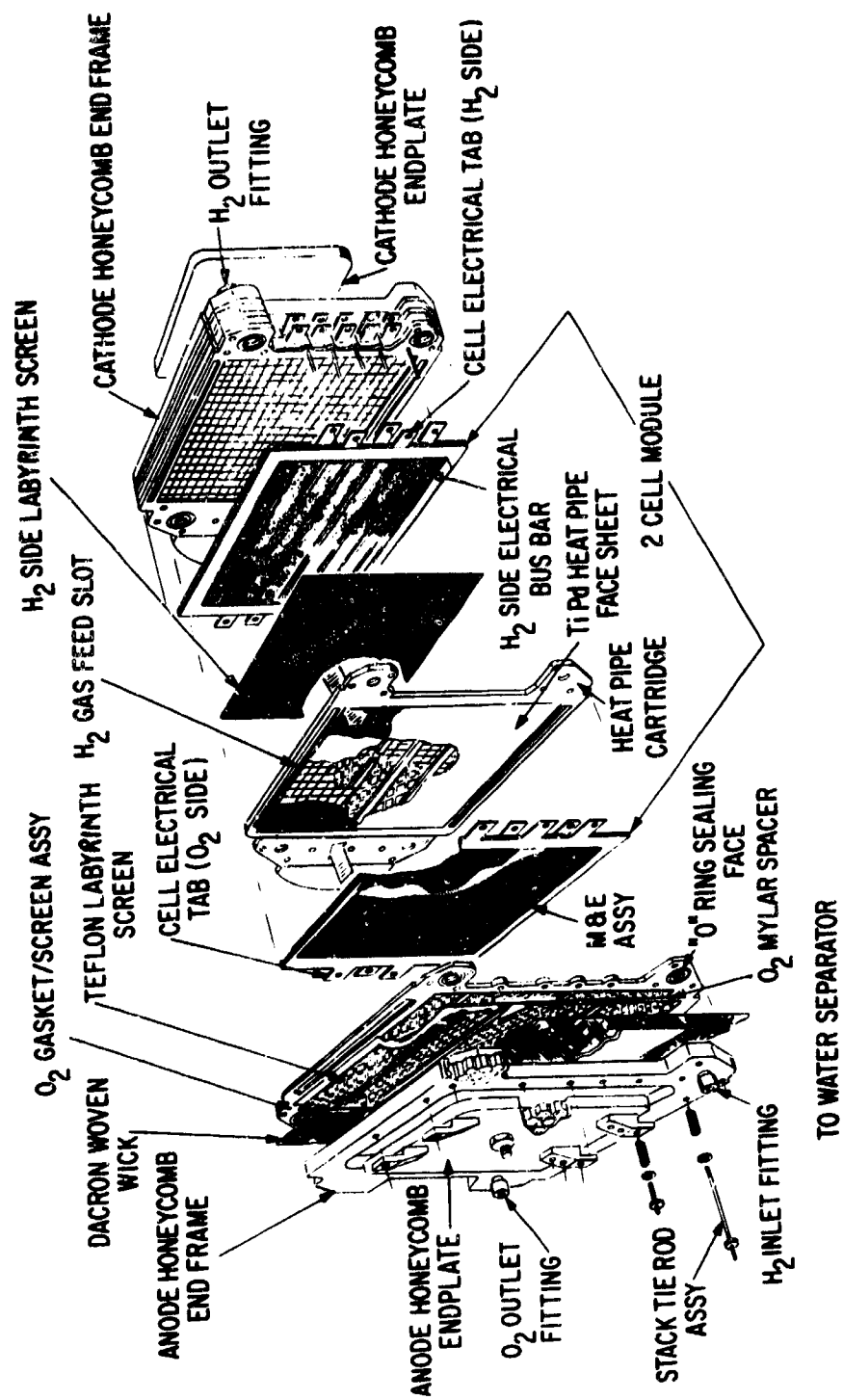


Figure 13. Regenerative Fuel Cell Stack Component Parts

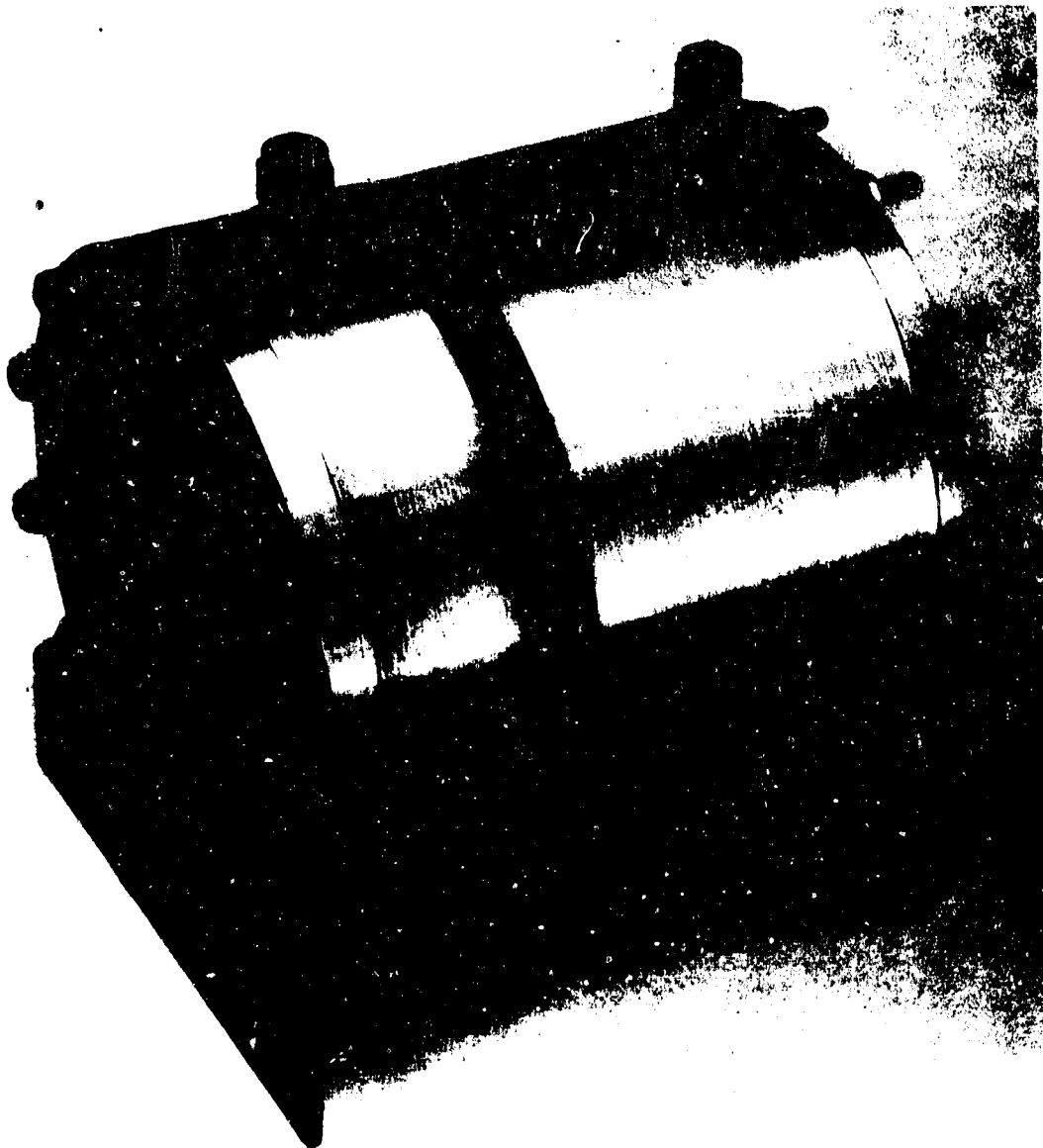
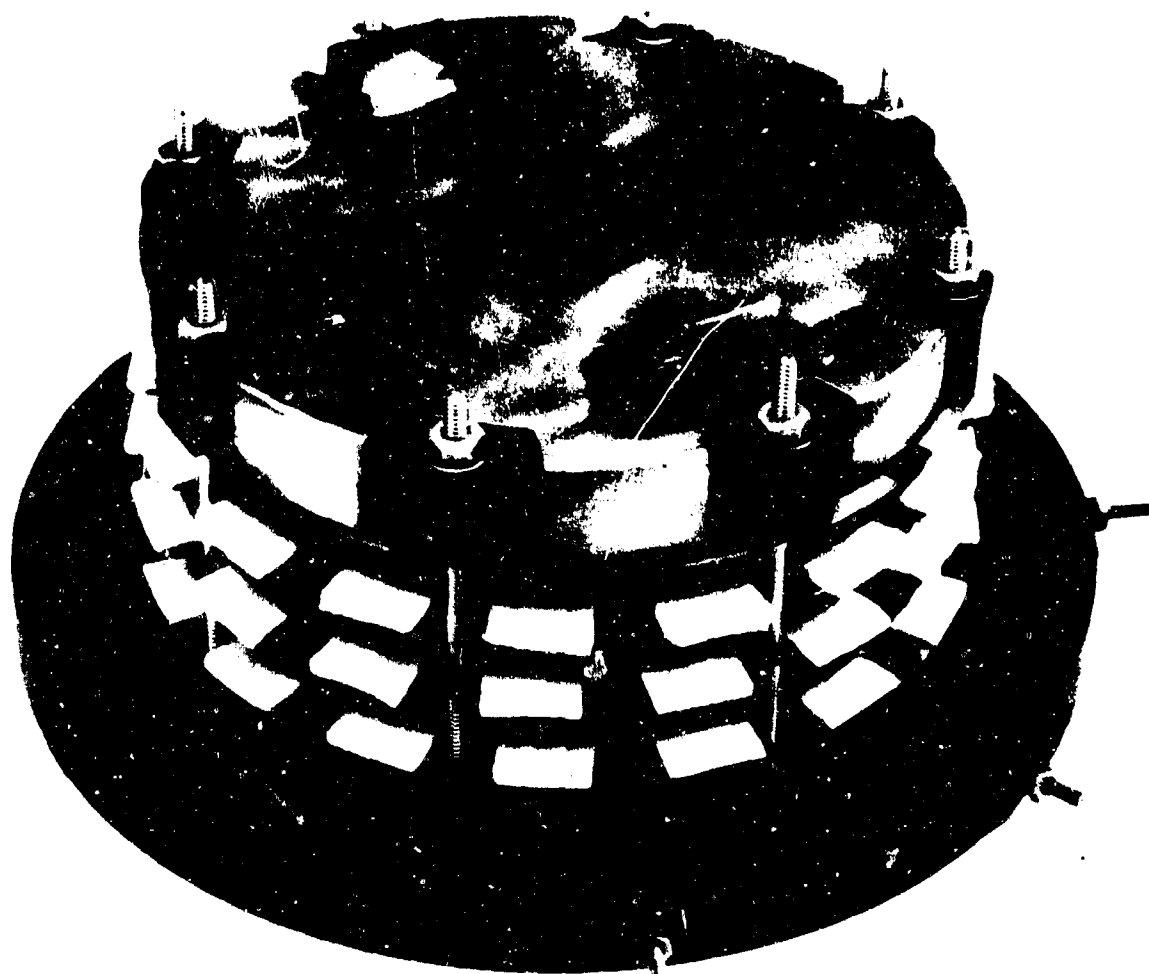


Figure 14. Electrolysis Stack Test Unit



one inch

Figure 15. 3-Cell Electrolysis Stack Configuration

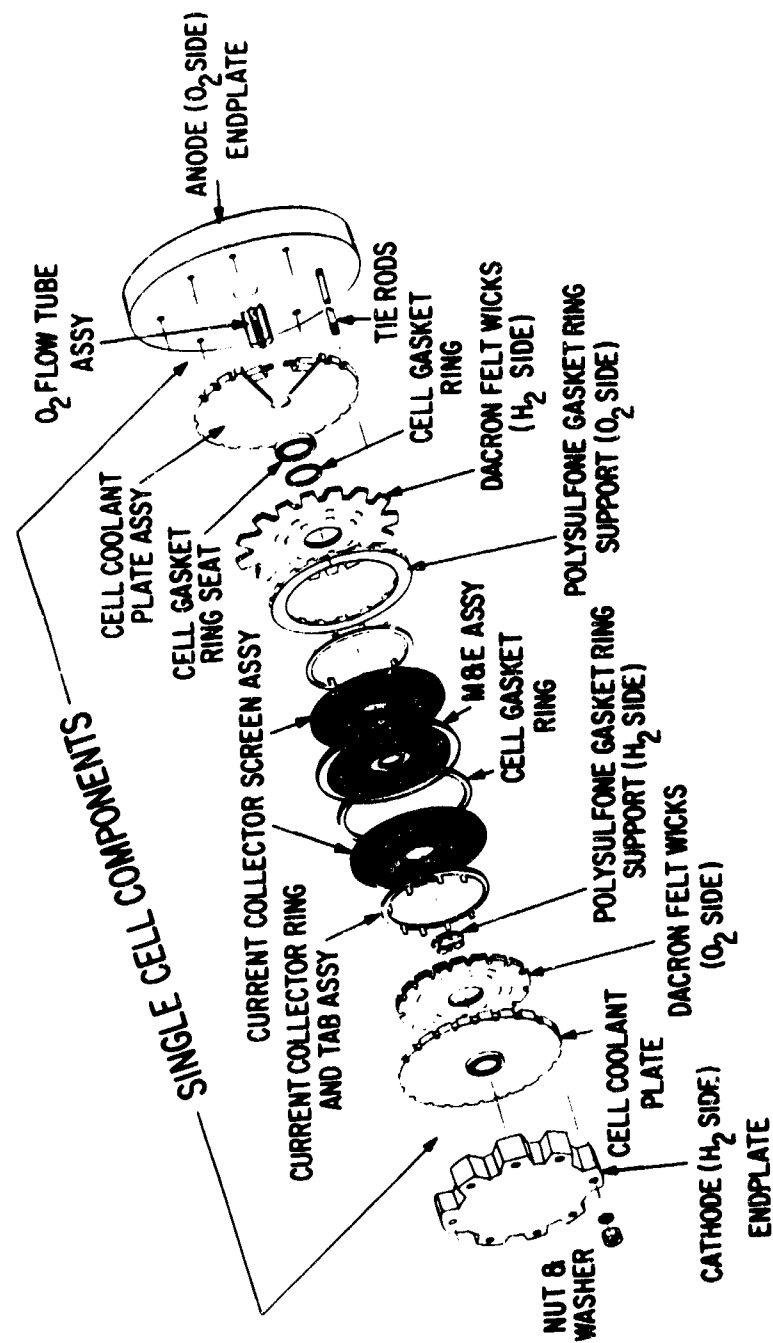
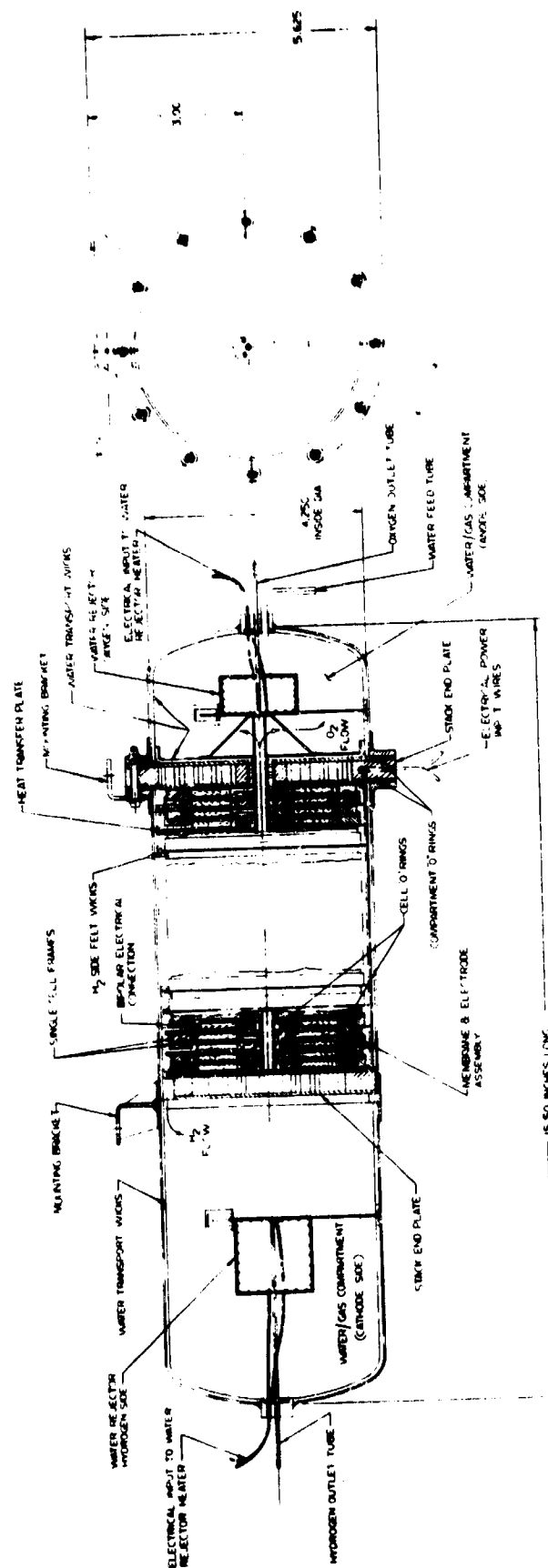


Figure 16. Electrolysis Unit Component Parts



[illegible]

**Figure 17. Integrated Electrolysis Unit Flight Prototype**

During this program a complete 150-200 watt breadboard regenerative fuel cell system was designed and fabricated, utilizing a 3-cell electrolysis unit and a 6-cell fuel cell stack (see Figure 18). The gas reactant storage tanks and gas regulators were mounted in the upper part of the test stand (see Figure 19) with the fuel cell stack packaged in a breadboard test case below this gas storage section. The electrolysis unit, associated gas controls and a breadboard deionizer unit are mounted in the lower third of the stand. Flexibility was incorporated in the test setup to operate the fuel cell and electrolysis units independently of each other or as an integrated regenerative system. Figure 20 is the fluid flow schematic of the test setup which identifies all components piping and locations within the test facility for operation of the system (see also Table II). Appendix III gives the operating instructions for the breadboard system generated during the program. These instructions are included for record purposes in the event the system is reactivated.

Throughout the program a continuing effort was made to reach the system design objective of 35 watt-hr/lb. Table III lists the changes in system weight during the program with a final estimated system weight (October 1969) of 46 lb. This results in an estimated flight prototype system energy density of 26 watt-hr/lb. As noted from Table III, 50% of the weight is attributed to the fuel cell stack with more than 50% of the overweight compared to the specification target accountable in the stack. The system components are not visualized to be further weight-reduced at the present state of development. With the addition of redundant components to insure high system reliability, it is currently estimated that a system energy density above 20 watt-hr/lb can be obtained with the integrated regenerative system concept.

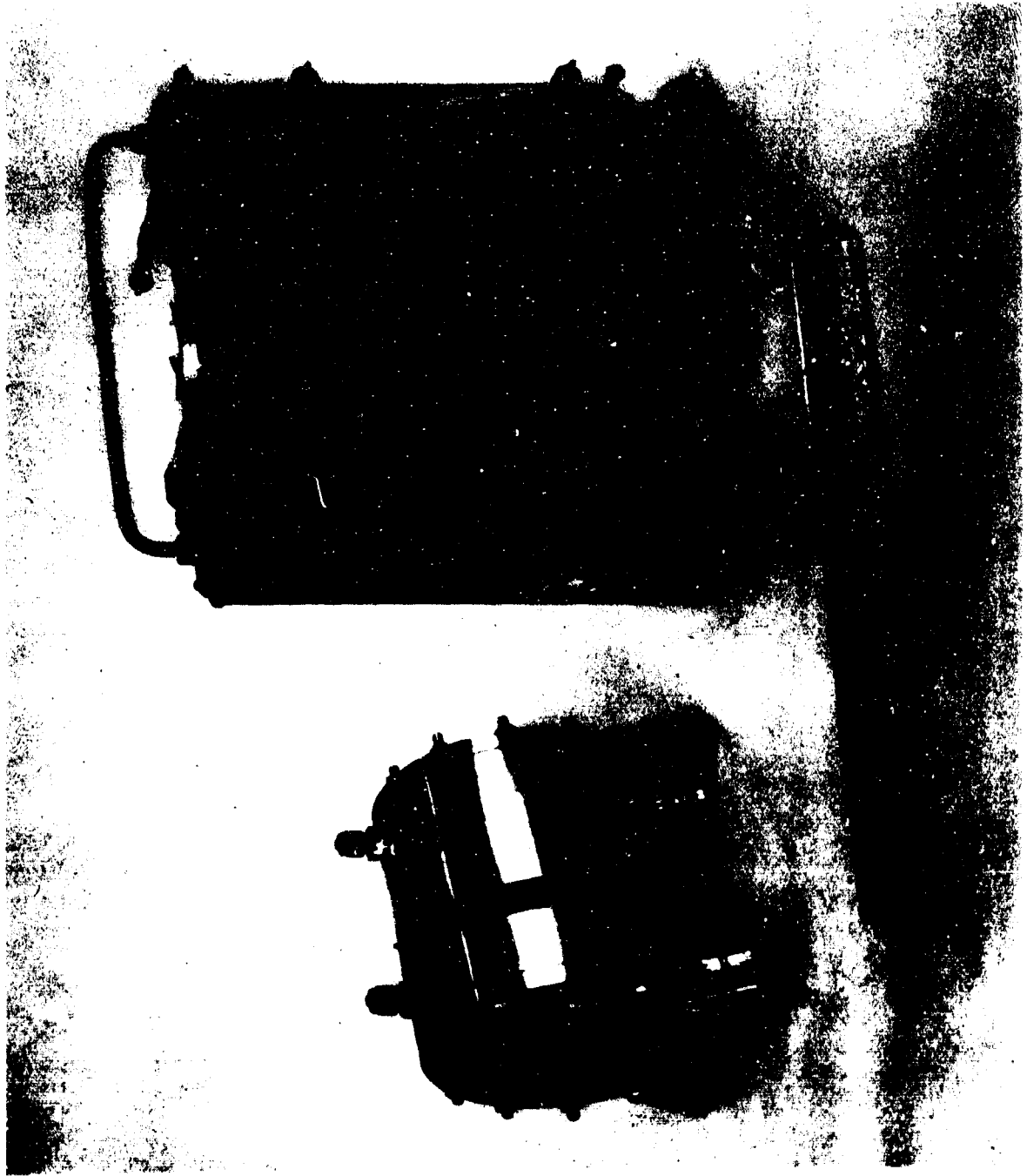


Figure 18.    Electrolysis and Fuel Cell Units of Regenerative Fuel Cell System

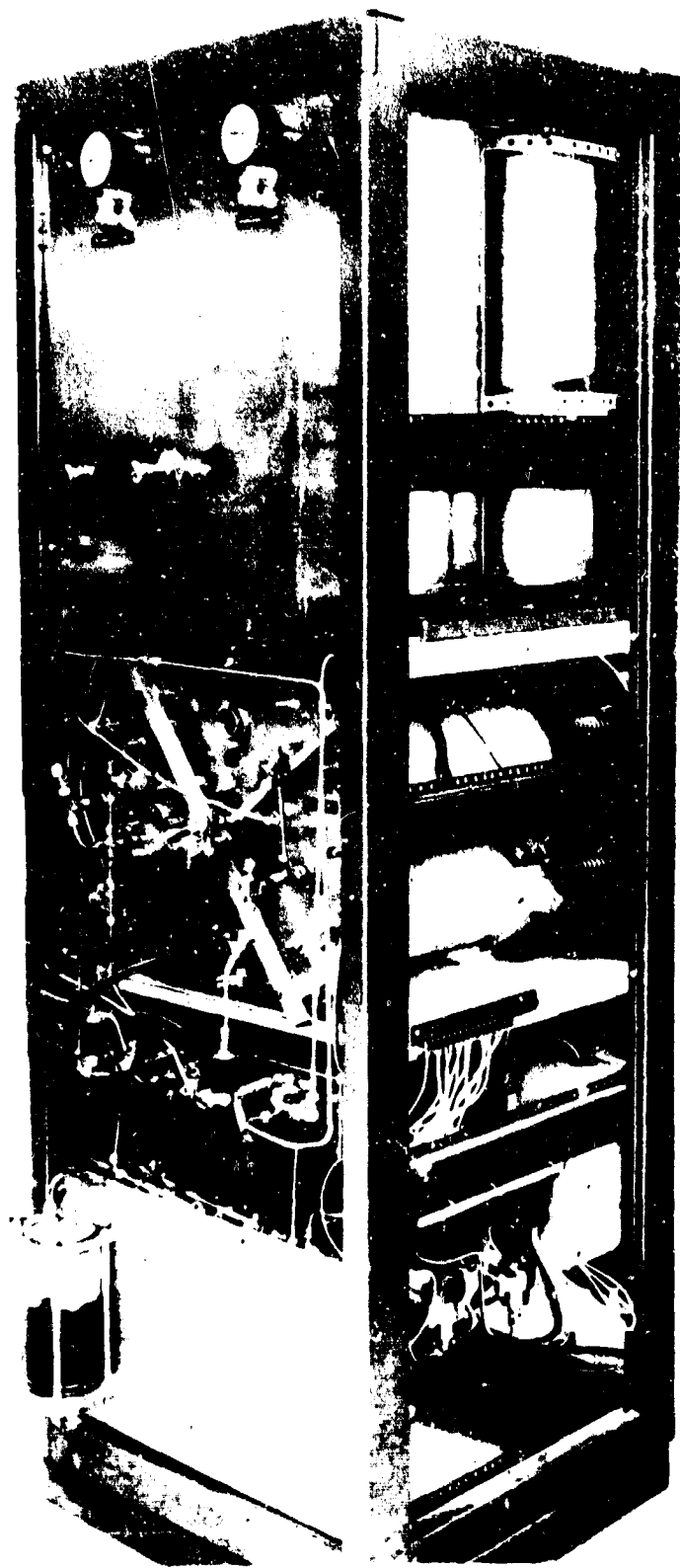


Figure 19. Breadboard Regenerative Fuel Cell System Test Setup

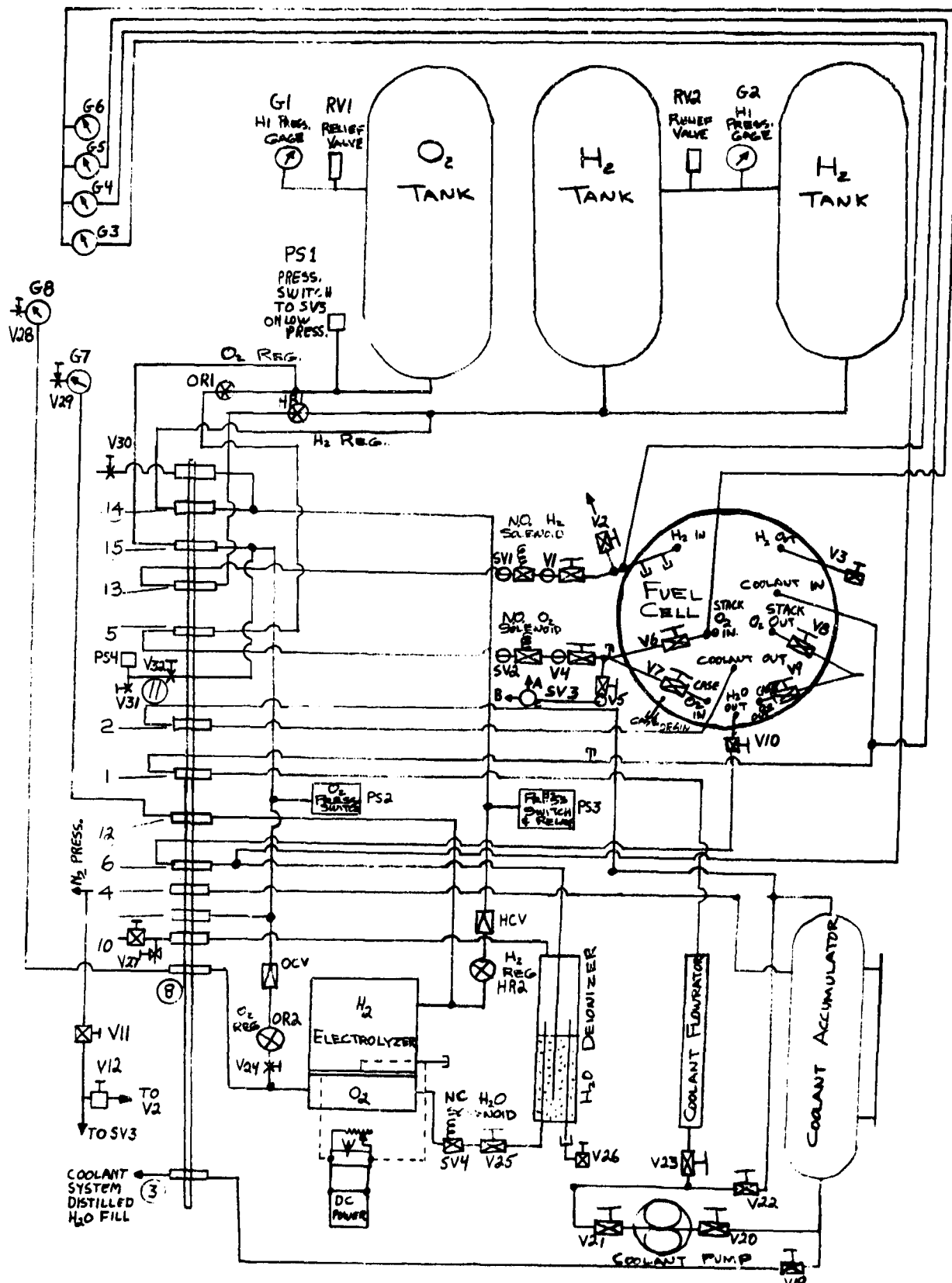


Figure 20. Regenerative Fuel Cell System Breadboard Fluid Flow Schematic

**Table II**

**Breadboard Regenerative Fuel Cell System Component Identification**

<u>Item Number</u>	<u>Description</u>
V1	H <sub>2</sub> In Valve System Gas
V2	H <sub>2</sub> In Valve Facility Gas
V3	H <sub>2</sub> Out Valve
V4	O <sub>2</sub> In Valve System Gas
V5	O <sub>2</sub> In Valve Facility Gas
V6	O <sub>2</sub> Stack In Valve
V7	O <sub>2</sub> Case In Valve
V8	O <sub>2</sub> Out Stack Valve
V9	O <sub>2</sub> Out Case Valve
V10	Product H <sub>2</sub> O Out Valve
V11	N <sub>2</sub> Valve
V12	N <sub>2</sub> Valve
V19	Coolant System H <sub>2</sub> O Fill Valve
V20	Coolant Pump In Valve
V21	Coolant Pump Out Valve
V22	Coolant Flow Control Valve
V23	Coolant Bypass Flow Valve
SV1	H <sub>2</sub> Solenoid Valve N.O.
SV2	O <sub>2</sub> Solenoid Valve N.O.
SV3	O <sub>2</sub> Solenoid Valve 3-Way N.O.
PS1	Pressure Switch Set at 50 psig
PS2	O <sub>2</sub> Pressure Switch shuts off electrolyzer power where O <sub>2</sub> Tank pressure reaches 145 psia.
PS3	H <sub>2</sub> Pressure Switch " " " " " H <sub>2</sub> " " " " "
OR1	System Oxygen Regulator
HR1	System Hydrogen Regulator
G1	Oxygen Tank Pressure
G2	Hydrogen Tank Pressure
RV1	Oxygen Tank Relief Valve
RV2	Hydrogen Tank Relief Valve
V24	Manual Shutoff for Elect. O <sub>2</sub> Installed Because of Leak in OCV
V25	Water Transfer Valve
V26	Deionizer Drain Valve
V27	Deionizer Pressure Relief Valve (Not Presently on Unit)
V28	Instrument Valve May be Used for System Evacuation O <sub>2</sub> Side
V29	Instrument Valve May be Used for System Evacuation H <sub>2</sub> Side
OCV	Automatic Check Valve O <sub>2</sub> Side
HCV	Automatic Check Valve H <sub>2</sub> Side
V30	High Pressure H <sub>2</sub> Vent Valve (Storage Tank)
V31	High Pressure O <sub>2</sub> Storage Tank Vent Valve
V32	High Pressure O <sub>2</sub> Valve
SV4	Water Transfer Solenoid Valve
W1	Electrolyzer Power Switch
A1	Ammeter
G3	O <sub>2</sub> > H <sub>2</sub> O Pressure Gage
G4	O <sub>2</sub> > H <sub>2</sub> Pressure Gage
G5	O <sub>2</sub> - Coolant Pressure Gage
G6	O <sub>2</sub> Case Pressure Gage
G7	Elect. H <sub>2</sub> Pressure Gage
G8	Elect. O <sub>2</sub> Pressure Gage

Table III  
System Component Weight Changes During Program

Item No.	Component	Proposal	Spec. Target	Wt. (3/15/69)	Wt. (7/10/69)	Wt. (10/30/69)	Δ Weight Spec. vs. 10/30/69
1.	Fuel Cell Stack and Container	15.31	15.3	23.2	23.2	23.2	+ 7.9
2.	Water (including est. 100% excess)	2.2	2.2	2.2	2.2	2.2	0
3.	Ion Exchange Bed	-	1.9	1.9	1.5	1.5	- .4
4.	H <sub>2</sub> Storage Tank	4.37	8.5	5.1	6.2	8.1	
5.	O <sub>2</sub> Storage Tank			3.4	2.3	3.7	+ 3.3
6.	System Wicking		1.4	6.6	1.0	.8	- .6
7.	Electrolyzer Container	.58	2.0	2.0	1.8	1.8	-.2
8.	Electrolyzer Stack		1.0	2.0	2.8	2.9	+ 1.9
9.	Valves, Regulators and Piping	2.0	2.0	2.0	2.0	2.0	0
	TOTAL	24.46 lb.	34.3 lb.	48.4 lb.	43.0 lb.	46.2 lb.	+ 11.9

10. Energy-to-weight ratio (watt-hr/lb)      49.0      35.0      24.8      27.9      26.0

#### 4.0 COMPONENT/SYSTEM TESTING

##### 4.1 Component Fuel Cell Stack Testing

During the program a total of four fuel cell units were tested, with the design objective of demonstrating performance and life capability of the basic module configuration at the design point condition of the regenerative system. Testing was conducted on a continuous basis at 100 ASF (35 amps) with the operating temperature initially at 180°F and which was subsequently changed to 150°F for improved stack reliability. All testing was conducted at approximately 35 psig gas pressures.

A single module containing two cells (Serial No. 10-1-1) was first subjected to a life test (17 July 1969) at the 180°F temperature level. Testing was terminated after approximately 321 load hours on 21 July 1969, when gross distortion of the epoxy glass end plates resulted in the loss of a gasket seal between the hydrogen and oxygen manifolded cell gases. Cell performance was normal during the life test as illustrated by Figure 21. Failure analysis resulted in the substitution of titanium end frames in the design.

A second single module (Serial No. 11-1-1) was placed on test in October 1969 and subjected to a life test at 180°F. Testing was abruptly terminated at the 540 hour load time point (407 hours at design load condition) by loss of performance of Cell No. 1 and subsequent failure of both cells with gas pressure equalization across the membrane. Failure occurred about 20 minutes after a hydrogen and oxygen purge. Examination of the recorded test data revealed no abnormal test condition or indication of an imminent unit failure prior to loss of the unit. Figure 22 illustrates the performance of the module during the testing at 180°F and 100 ASF.

It was concluded from the failure analysis of the component parts and review of the test data that no clear explanation can be made of this failure. The presence of the incorrectly bonded membrane causing a potential oxygen leak path to the hydrogen inlet side could have resulted in the failure, although the examination of the membrane showed no evidence of this occurrence compared to previous teardowns.

Planned test corrective action taken was first to eliminate humidification of the hydrogen gas prior to introduction to the unit. This step was based on laboratory experience where the longest operating cells were on dry gas. The operating stack coolant temperature was also lowered from 180 to 150°F since system analysis had shown only a loss of approximately 0.5% in system energy efficiency to achieve a projected operating life increase on the membrane.



A 4-module fuel cell unit (Serial No. 12-4-1) was placed on test in November 1969 for life testing at 150°F coolant temperature. Upon introduction of hydrogen and oxygen gases, the unit failed to maintain open circuit voltage. Subsequent teardown and analysis revealed a failed membrane (Module No. 1) with a pinhole opposite a broken gold screen strand.

It was concluded from the failure analysis of the component parts and review of the test data that the presence of the membrane pinhole could not be clearly attributed to any one of the following possible causes:

- a) The broken gold electrode screen strand punctured the membrane sometime during the manufacture, assembly or test cycles.
- b) The intermittent electrical short caused the pinhole type burnout of the membrane by locally overheating the cell in a weak spot.
- c) A pinhole flaw existed in the original membrane material which could not be detected by the standard leak check assembly and test procedures.

The following corrective actions were taken during the reassembly of the remaining three modules into a fuel cell stack:

- a) Conduct a stack gas leakage test at 10 psig oxygen over hydrogen side pressure for 30 minutes, in addition to the standard 3 psig differential pressure test.
- b) Substitute Teflon sleeving on the stack tie rods for the Nylon shrinkable tubing which can be easily cut resulting in potential electrical shorts.
- c) Substitute thicker and wider polysulfone insulating washers between the hydrogen and oxygen electrode tabs to prevent potential electrical shorting.

The fuel cell unit (Serial No. 12-3-1) was subsequently placed on test in December 1969 for a 200-hour life test prior to mission cyclic load testing (see Figure 23). The unit was next subjected to extended open circuit conditions between daily one-hour load applications to evaluate stack performance as applicable to the regenerative system with a total life accumulation of approximately 250 hours, with about 700 hours on active gases. This unit was subsequently assembled into the regenerative breadboard system for system testing.

The final fuel cell unit (Serial No. 13-4-1) consisting of four modules (eight cells) was placed on test in April 1970 and life testing initiated at 150°F and 100 ASF. Figure 24 shows the performance of the unit prior to failure at the 975 hour life point. Teardown of the unit revealed a pinhole in the membrane at the hydrogen inlet side of Cell No. 5 of Module 3. The unit catalytic burner indicated that burning

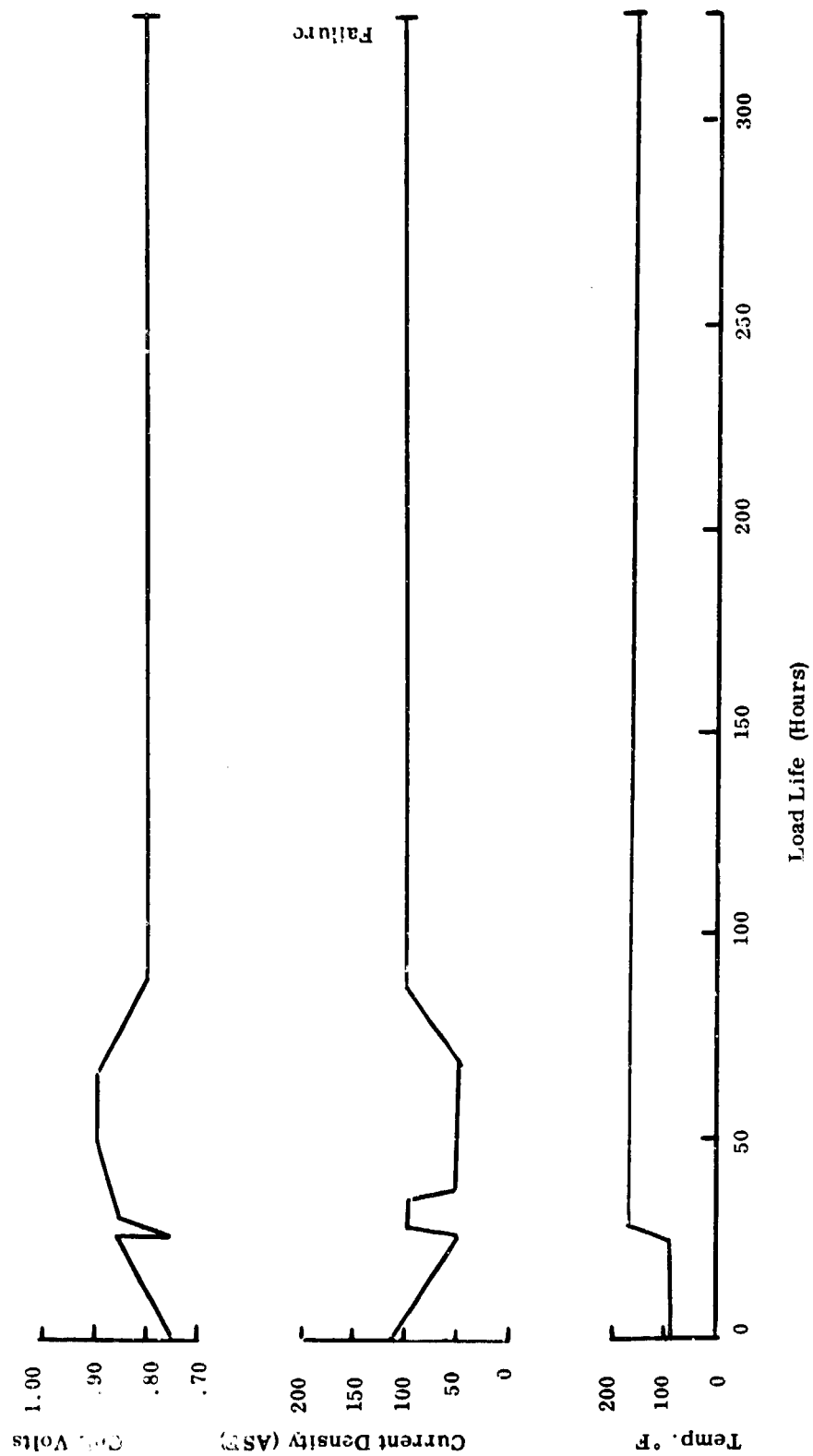


Figure 21. Single Fuel Cell Module Testing (Cell Serial No. 10-1-1)

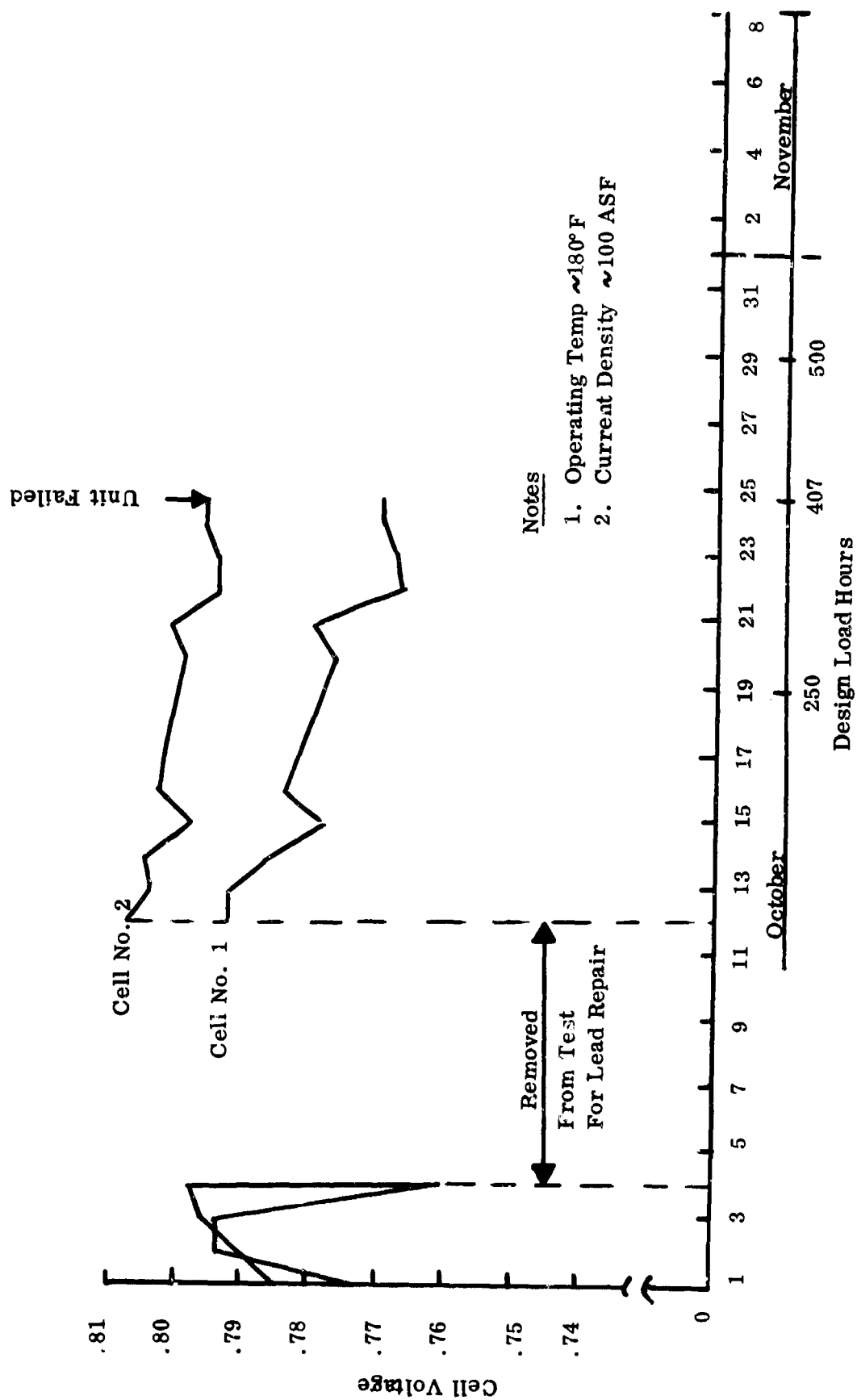


Figure 22. Single Fuel Cell Module Testing (Serial No. 11-1-1)

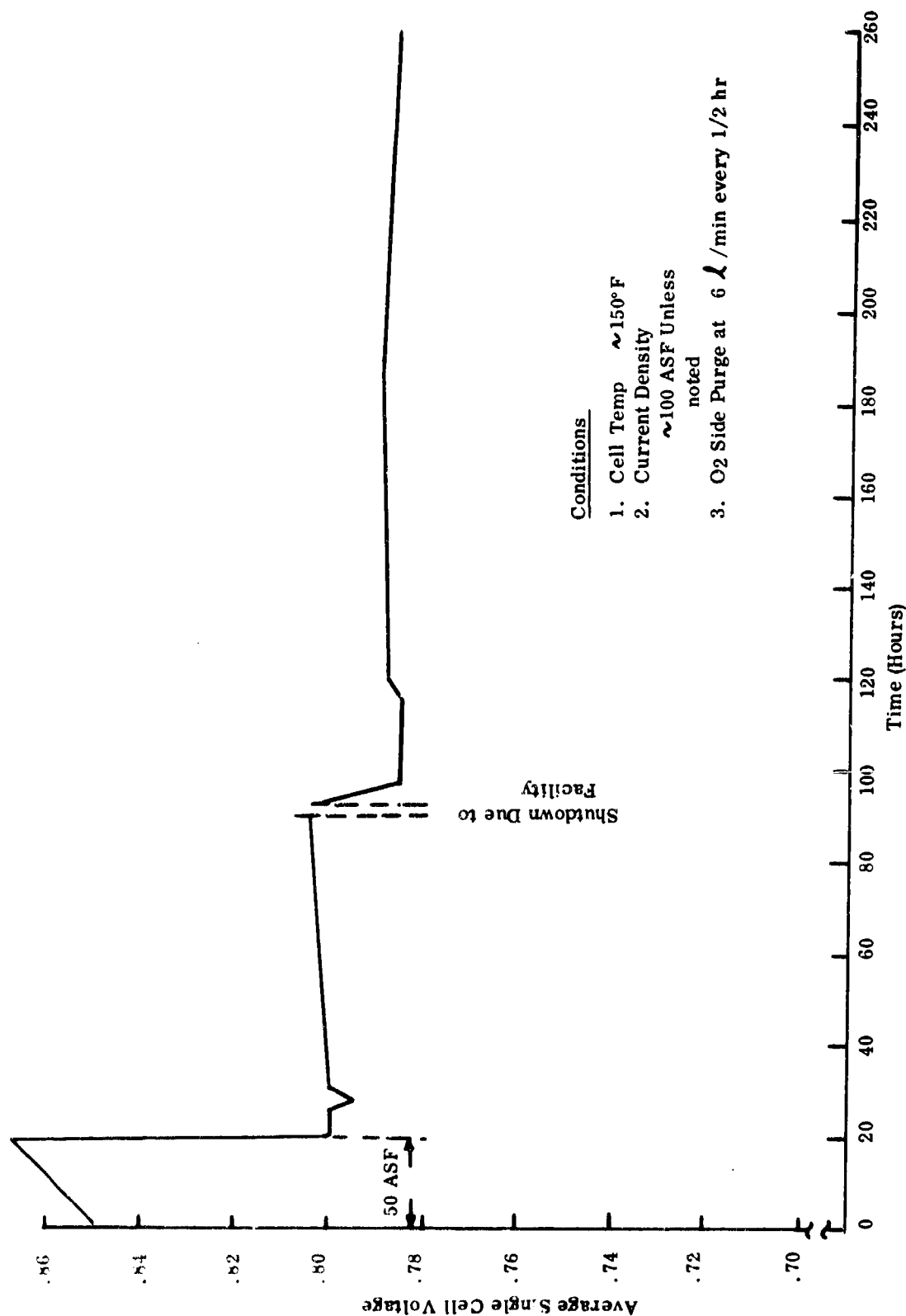


Figure 23. 3-Module Fuel Cell Unit (Serial No. 12-3-1) 200-Hour Endurance Test

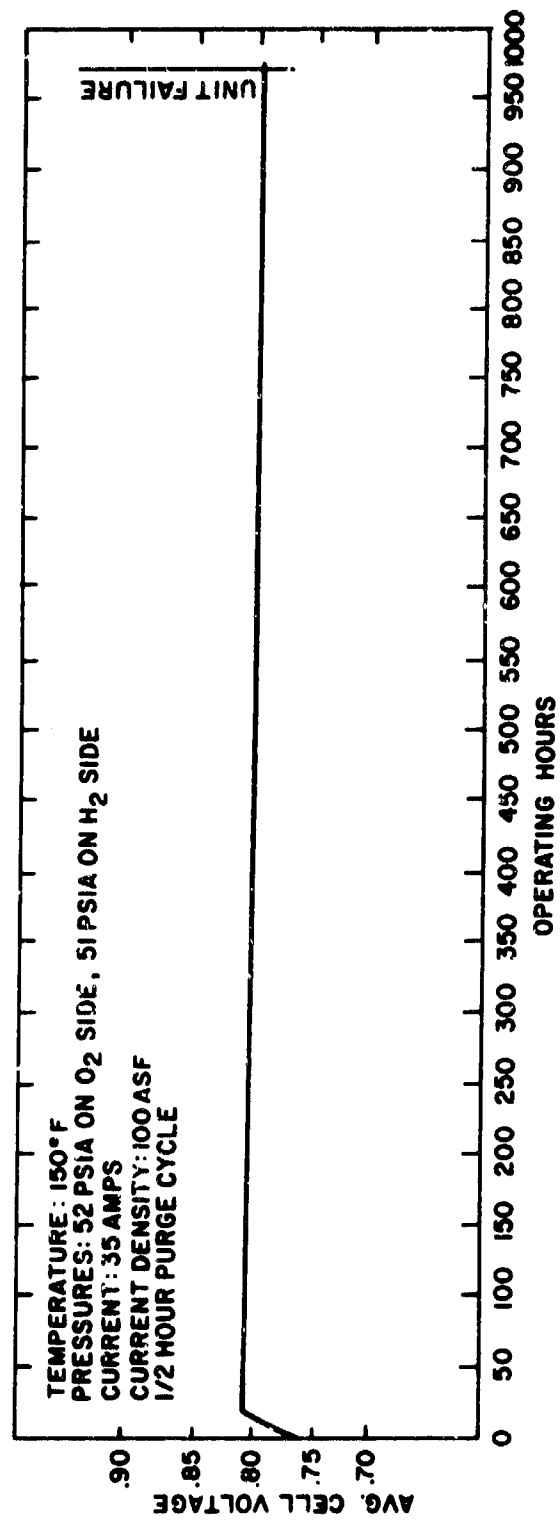


Figure 24. Life Testing of 8-Cell Fuel Cell Unit (Serial No. 13-4-1)

occurred upstream of the inlet check valve, with all other cells appearing normal. Analysis of the test facility hydrogen gas revealed excessive amounts of oxygen in the gas supply. It was concluded from the failure analysis that the presence of the membrane pinhole could be attributed to any one of the following possible two causes:

a) The presence of high amount of oxygen in the hydrogen gas caused failure of the cell by burning at the cell membrane. An excessive amount of water in the catalytic burner area made the burner ineffective.

b) Location of failure is known to be a highly stressed area of the cell configuration due to the particular operating conditions of this application. The cell H<sub>2</sub> inlet location is considered to be a potential end-of-life failure point.

#### 4.2 Component Electrolysis Stack Testing

Prototype electrolysis testing was first conducted on a single cell in August 1969 with a Pt-5% Ir catalyst structure on the oxygen evolution side of the membrane. A performance level of 1.86 volts was obtained at the 5 amp level (128 ASF) at room temperature conditions. Evidence of excessive cell drying due to continual rising of cell voltage after repeated wetting was seen. The unit was tested with the cell in the vertical position, causing water transport problems. A total operating time of 53 hours was accumulated prior to unit removal from test for design modifications and test facility improvements.

The degree of wetness of the hydrogen side wicking indicated that water was not moving into the center of the wicking rapidly enough to keep the wicks saturated. It was hypothesized that evolved gas was filling the wicks during electrolysis and thereby reducing their wicking capability.

The following changes were made to provide a gas path that would permit the evolved gas to move away from the catalytic surface during electrolysis and to facilitate return during fuel cell operation:

a) A second double screen assembly was added to the assembly adjacent to the cell catalytic surfaces, thus providing a 12 mil screen gap between the wick and catalyst similar to the laboratory hardware. Compression tests between 6 and 12 mil gaps were evaluated by the laboratory.

b) A number of 1/16 inch wide notches were cut in the three layers of wicking nearest to the cell catalytic surfaces to provide gas paths in and out of the enclosed cell volume.

In addition to the above modifications, the flanged heat conductor plate was redesigned to provide better cell cooling.

Testing procedure was also modified to permit testing with the cell surface horizontal rather than vertical. This will provide a better simulation of zero "g" operation than occurs when the cell surface is vertical and all the water accumulates at the bottom of the cell container. With the cell surface horizontal, the operating temperature should be uniform across the cell.

Testing was continued on the unit to evaluate performance in both the fuel cell and electrolysis mode. Fuel cell operation of the unit was possible with this improved gas flow configuration, resulting in 0.17 volt at 23.4 ASF and 0.5 volt at 13.0 ASF at 75 psia gas pressures and 90°F temperatures. This performance was obtained with the surface of the cell vertical. In this position, part of the cell was masked by liquid water within the gas compartments, resulting in an actual current density much higher than indicated and consequently lower indicated performance. Under normal operating conditions with a prescribed quantity of water, this would not occur as all of the free water would be consumed in electrolysis before the fuel cell operation was initiated.

During these initial tests it was also noted that large quantities of water were being transported to the hydrogen gas storage tank and thus were unavailable for electrolysis. After 4.5 hours of operation, the cell developed a short and testing indicated a hole in the membrane. Failure analysis of the cell showed a pinhole had developed in the cell area adjacent to one of the electrical connector tabs carrying current from the screens in contact with the cell electrode to the metal collector plate. The cause of the failure was considered to be local overheating due to loss of water resulting in membrane failure. The lack of water was due to excessive water transfer to the H<sub>2</sub> tank.

To overcome this deficiency, the internal water passages of the unit were modified to reduce water entrainment and test procedures were modified to reduce the rate of hydrogen gas removal by substituting automatic pressure relief valves to vent gas and maintain the desired unit operating pressure. Subsequent testing has shown very little water transport to the tank.

After disassembly of the failed unit, it was determined that there had been an incorrect assembly which accounted for its observed poor performance. The gold screen on the hydrogen electrode had been omitted and the catalyst for the two electrodes had been reversed, resulting in a 100% Pt catalyst on the O<sub>2</sub> side and a Pt-5% Ir catalyst on the H<sub>2</sub> side.

A new cell was manufactured with a tantalum screen substituted for the niobium screen imbedded in the catalyst on the O<sub>2</sub> side. This change was made to prevent buildup of oxidation between screen and catalyst and the resultant resistance losses as observed in the laboratory testing of the 3 x 3 inch units. Operation of this cell with the correct membrane and electrode assembly resulted in a significant

electrolysis performance improvement. This cell at 180°F and 166 psia pressure required 1.68 volts at 133 ASF after 3 hours of operation with the membrane in the horizontal H<sub>2</sub> side up orientation.

The best fuel cell operation obtained was 0.73 volt at 1.83 amps (77 ASF). It should be noted, however, that the absolute level of fuel cell performance is not critical since its only function during this mode is to evacuate the oxygen and hydrogen side of the electrolysis unit for transport of water from the fuel cell.

After 40 hours of testing, a temperature controller was installed into the test setup to permit unattended operation. The test facility was also equipped with an overvoltage trip to remove the electrolyzing power source if the input voltage exceeded an arbitrary 1.97 volts based on laboratory test experience.

On the first attempt at unattended operation, the overvoltage trip removed power from the electrolysis cell. The apparent cause of the high voltage in the cell was a faulty electrical wall socket connection that caused the unit heating tape on the case to lose power, thus the unit operating temperature lowered with a corresponding normal rise in input voltage to over 1.97 volts. When the unit was first observed seven hours after this occurrence, the H<sub>2</sub> pressure had diffused down to 57 psia and the O<sub>2</sub> to 120 psia, resulting in a 60 psia gas differential across the membrane. Upon initiation of the testing the cell subsequently developed a cross-membrane leak which resulted in some internal burning but no serious damage to the hardware. Figure 25 illustrates the unit performance during the testing.

Failure analysis revealed that the hole in the membrane was adjacent to the current collection metal tab connecting the cell screen assemblies with the cell heat transfer plates. Since only two of these tabs were designed into each screen assembly it may have resulted in an uneven flow of current and heat from the membrane causing a poor distribution of water within the membrane. This structure weakened the membrane in this area. To overcome this deficiency the two tabs were replaced by a 3 mil thick niobium ring 2.15 inch OD and 1.9 ID matching the current collection ring imbedded in the O<sub>2</sub> side catalyst of the cell assembly. This ring has eight tabs equally spaced around it which extend through the wicking and are welded to the heat transfer plate. The tabbed ring is welded in turn to the four layers of niobium screening which maintain the 0.012 inch gas gap. The screen and ring assembly was platinized to prevent buildup of electrical contact resistance between any of the current carrying components.

A 3-cell electrolysis stack was placed on test in January 1970 with the above indicated changes and with an improved catalyst structure in the membrane and electrode assembly. This electrode substitution was a result of continued GE/DECBS Fuel Cell Laboratory development efforts. Component testing was conducted on the unit to demonstrate performance prior to incorporation in the breadboard system. Performance was slightly higher than anticipated (approximately .030 volt/cell) but



was considered acceptable to be installed in the breadboard regenerative system. The measured gas generated from this test was low and was determined to be caused by excessive test facility piping leakage. Cell no. 2 performance was lower than the other two cells regardless of operating condition. An attempt was made to operate the unit in the fuel cell mode after the 12-hour third run but the stack was unable to hold 1 amp stably. It was decided to install the unit in the breadboard system and continue the checkout testing in the final test setup to evaluate this fuel cell problem in the electrolysis unit. Figure 26 illustrates the performance obtained in this checkout testing.

Figure 27 shows the two electrolysis runs in the breadboard system. During the second run, the current density was lowered for unattended operation overnight in order for personnel to be present the next morning to observe the completion of the electrolysis cycle. The amount of water initially added to the unit would have been consumed during the night. No attempt was made to store the gas in order to measure the gas production rate and compare the results to the anticipated rate. No indication of excessive facility gas leakage was observed during this run and the total amount of gas generated equaled the amount anticipated within the accuracy of the test equipment.

Figure 28 illustrates the fuel cell performance of the electrolysis unit in the breadboard system. It was determined from the testing that more gas volume was required on the hydrogen side of the electrolyzer in order to continue operation in the fuel cell mode for further oxygen side pressure reduction below the anticipated product water pressure. The system successfully transferred water from the main fuel cell stack side to the electrolysis unit after the electrolyzer oxygen side gas pressure was reduced by venting the pressure to the surrounding environment. Figure 28 illustrates the decay in the hydrogen side pressure of the electrolyzer during fuel cell mode operation of the unit. It will be noted that the hydrogen side pressure was below the oxygen pressure on run no. 2 after 120 minutes and further operation would only result in lack of hydrogen prior to the oxygen side attaining 30 psia for proper water transfer.

The electrolysis fluid circuit was modified in the breadboard regenerative system by the addition of a 565 cc gas bottle on the hydrogen outlet side of the electrolysis unit to increase the hydrogen gas volume. This assured that the decay in pressure on the hydrogen side of the electrolysis unit would not fall below the oxygen side pressure decay during the fuel cell mode of operation in the electrolysis unit. Figure 29 is a typical performance curve taken during one of a number of pressure decay tests conducted after the facility modification. The objective of this testing was to demonstrate the complete transfer of approximately 100 cc of product water made during the 72-minute main fuel cell stack operation from the system deionizer bed to the electrolysis unit oxygen side by consuming the generated oxygen gas in the electrolysis unit, thus lowering the pressure to a point below the water pressure for pressure transfer. All fuel cell type testing on the electrolysis unit was

unsuccessful due to test termination before obtaining the desired oxygen side electrolysis pressure (approximately 30 psia). The performance of cell no. 2 in the fuel cell mode decayed to a zero or negative condition as shown by Figure 29, thus preventing further operation in this mode. Current density on the unit had to be continually lowered during this mode to prevent negative cell operation. It is desirable to have as high a load on the unit as possible in order to complete this evacuation cycle prior to the electrolysis mode during the daily mission cycle time.

It was determined by laboratory testing that fuel cell operation of an electrolysis wicked unit configuration is considerably affected by the amount of water in the wicks adjacent to the electrodes. Cell No. 2 in the unit, being the lowest performer, was reasoned to be either water saturated or having poor wetproofing on the oxygen side electrode which would make it susceptible to fuel cell operation by product water drowning of the electrode on the oxygen side. This was demonstrated on the 3-cell electrolysis unit by alternately operating the unit in the electrolysis and fuel cell modes in an attempt to condition dry the electrode/wick system for proper fuel cell operation. The longer the unit was operated in the electrolysis mode, the longer the unit would operate in the fuel cell mode indicating a water saturation condition still existed in the unit. It was during this checkout testing that the 3-cell electrolysis stack failed. The unit had just completed a fuel cell mode run for 1 3/4 hours and in the process of electrically switching to open circuit the oxygen and hydrogen side gas pressures equalized at 60 psia from a 50 psi hydrogen-over-oxygen pressure differential condition. No noise was heard during the failure and from visual observation of the breadboard system and electrolysis unit, no damage was evident. The gas storage tanks were manually isolated from the electrolysis unit and the main fuel cell stack was disconnected from the breadboard gas tanks and external hydrogen and oxygen bottle gas applied to the unit.

The electrolysis stack was operated until the time of failure at approximately 130 ASF and 120°F between fuel cell mode type testing. Figure 30 illustrates the performance level of the unit and the generated hydrogen tank storage pressure during the unit checkout testing in the breadboard installation. Due to the unavailability of the final system size gas storage tanks, existing larger tanks were utilized resulting in the lower indicated hydrogen pressure at the end of the electrolysis mode instead of the design pressure of 166 psia. The lower electrolysis performance is a result of high cell and contact resistance and cell contamination observed during the failure analysis of the unit.

The 3-cell electrolysis stack was disassembled after failure in the regenerative system and the following visual observations were noted:

a) A high degree of discoloration and iron contamination was evident in the cell wicks from corrosion of the type 316 stainless steel tie rods and nuts within the unit.

b) The internal cell wicks and electrodes were dry, with evidence of water starvation from the wet felt wicking surrounding the stack.

c) The individual cell heat transfer cooling fin lips in contact with the unit case were stacked in such a manner as to pinch off some of the cell wicks leading to the hydrogen side, resulting in water starvation.

d) The water transport path on the oxygen side to the cell wicks was dry with evidence of water starvation.

e) Free water existed on the oxygen side of the case and the felt wick between this water and the oxygen side water transport path was water saturated.

f) The porous Teflon oxygen side water rejector was burned completely away on one side.

g) Excessive gas leakage was evident from each cell in the stack when the unit was submerged in distilled water and pressurized on the oxygen side.

h) No visual indications were present on the cell surfaces to show cell burnout or pinhole.

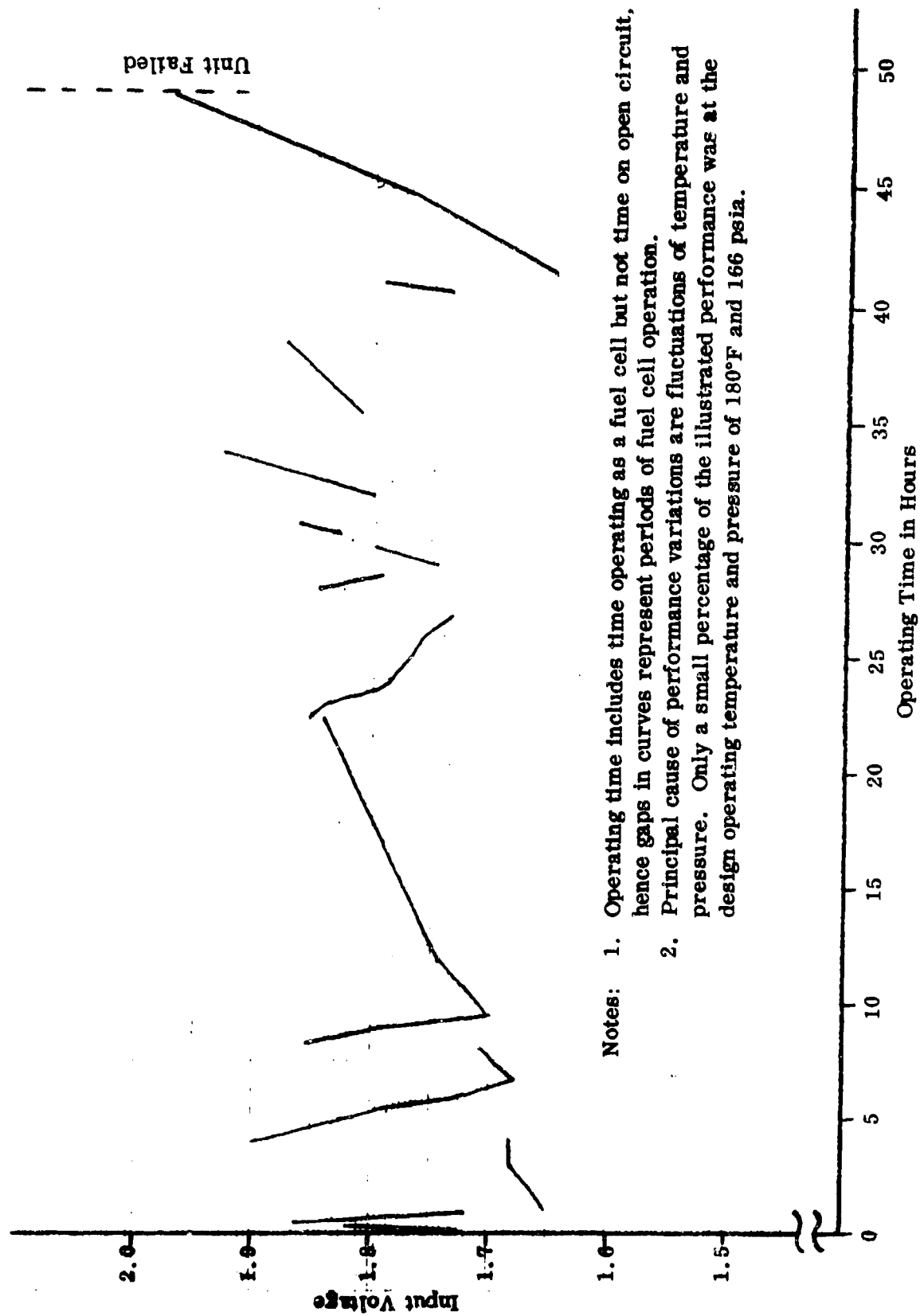
i) The edges of the cell current collector screens protruded through the polysulfone screen edge binder and pieces of this binder were missing.

j) The felt wick material would not rewet itself after the material was completely dried.

k) Essentially the same amount of torque was required to unload the stack tie rods as was required initially to assemble.

It was concluded from the failure analysis and review of the test data that the primary cause of failure was operation of the unit in a marginal dryness condition in attempting to resolve the fuel cell mode problem, coupled with an inadequate water feed system to the individual cells.

The 3-cell stack was reassembled with new cells in April 1970. Material changes were made in the unit to eliminate the iron contamination and the complete water transport system within the configuration was redesigned to improve water flow to and from the cells. Electrolysis unit checkout testing was continued in the breadboard system test stand resulting in approximately 100 hours of testing accumulated which demonstrated successful fuel cell mode of operation. Average cell performance was 1.70 volts at 80°F and 128 ASF. After completion of the unit checkout testing the 3-cell stack was connected to the remaining portion of the breadboard system for regenerative fuel cell system testing.



- Notes:
1. Operating time includes time operating as a fuel cell but not time on open circuit, hence gaps in curves represent periods of fuel cell operation.
  2. Principal cause of performance variations are fluctuations of temperature and pressure. Only a small percentage of the illustrated performance was at the design operating temperature and pressure of 180°F and 166 psia.

Figure 25. Electrolysis Cell Serial No. 2 Performance

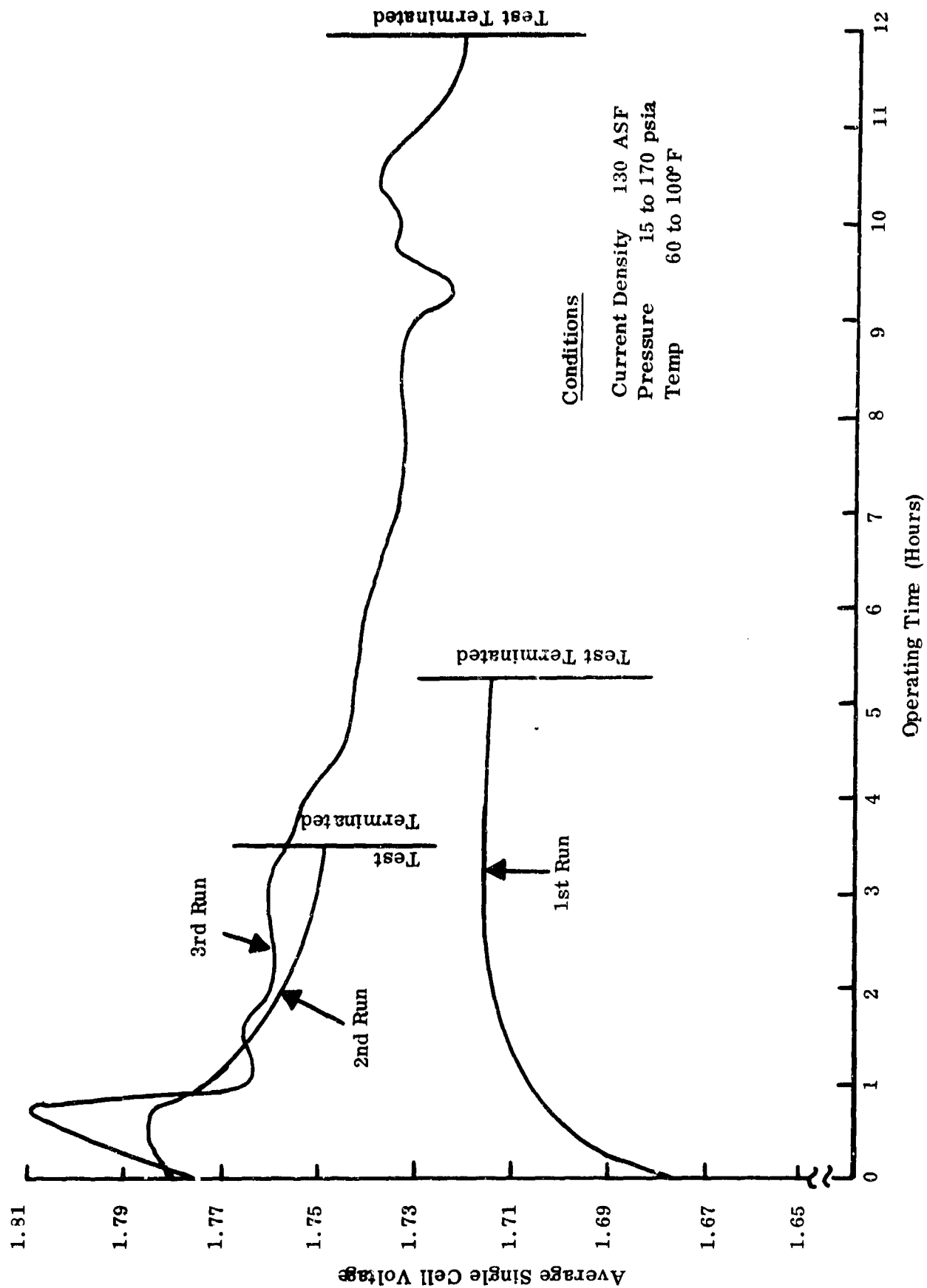


Figure 26. 3-Cell Electrolysis Stack Component Checkout Test

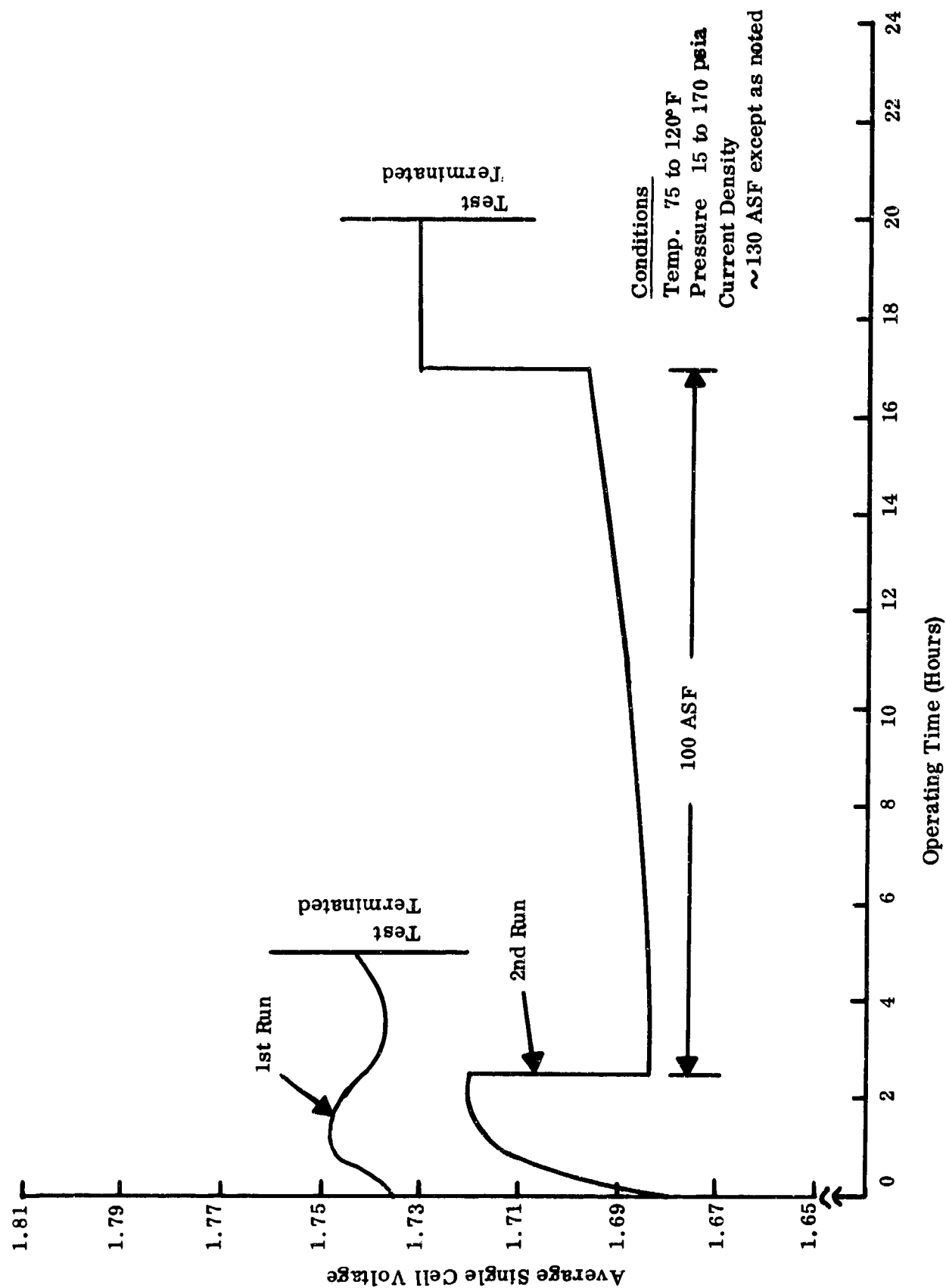


Figure 27. 3-Cell Electrolysis Stack System Checkout Test

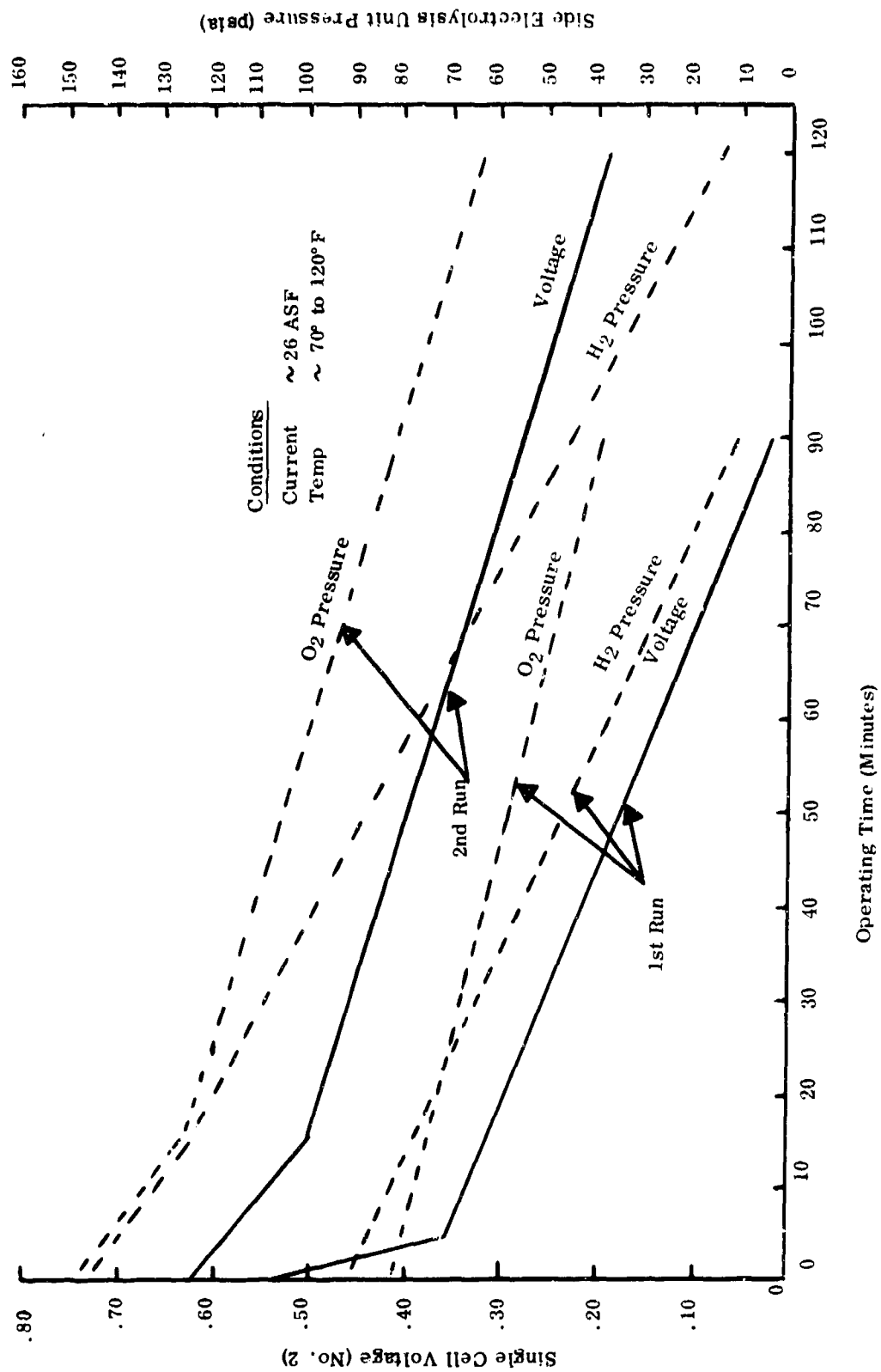


Figure 28. Fuel Cell Operation of Electrolysis Unit

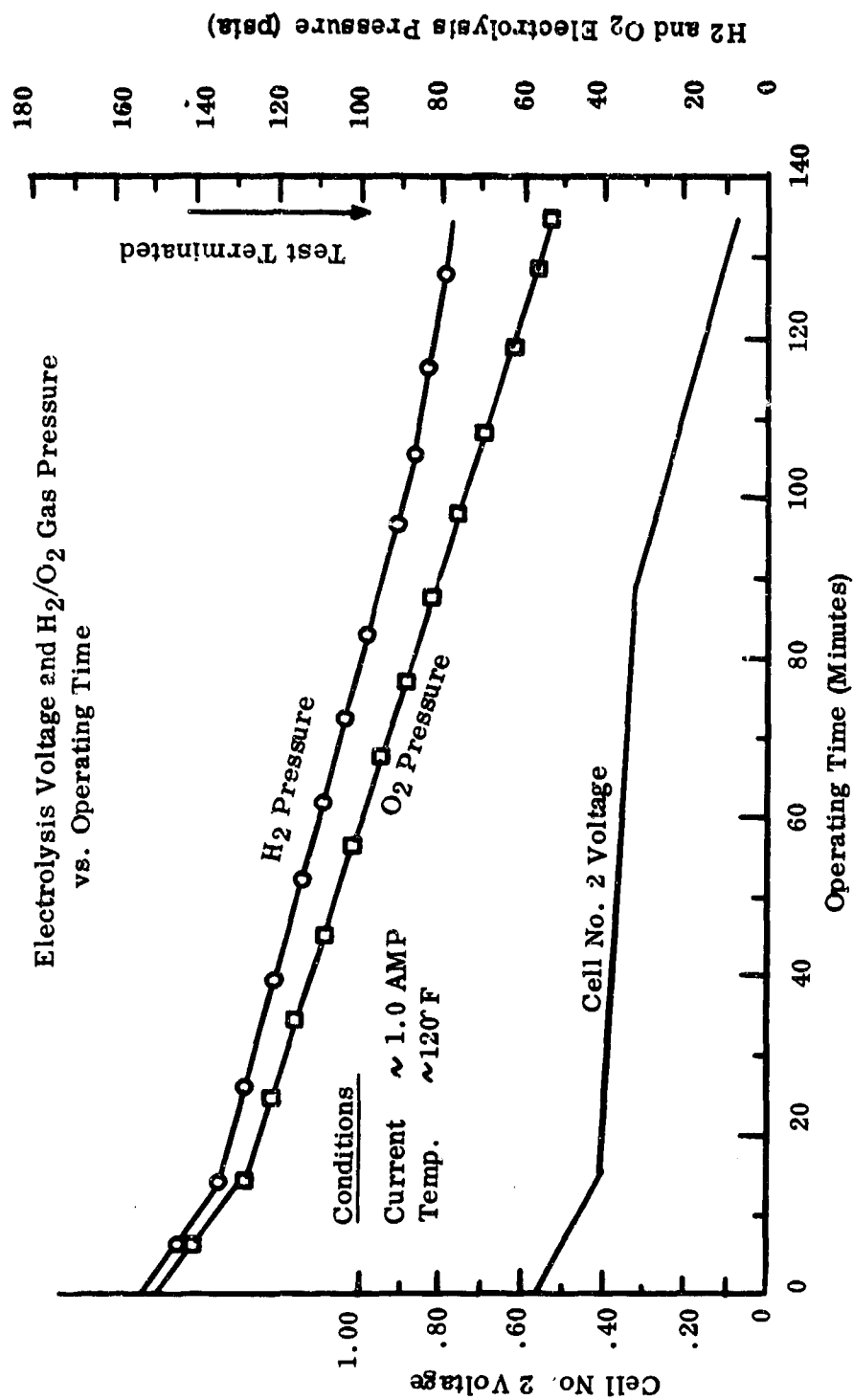


Figure 29. 3-Cell Electrolysis Unit Water Transfer Test -  
Typical Fuel Cell Operation



Electrolysis Cell Voltage, Electrolyzer and Tank Pressures  
vs. Time

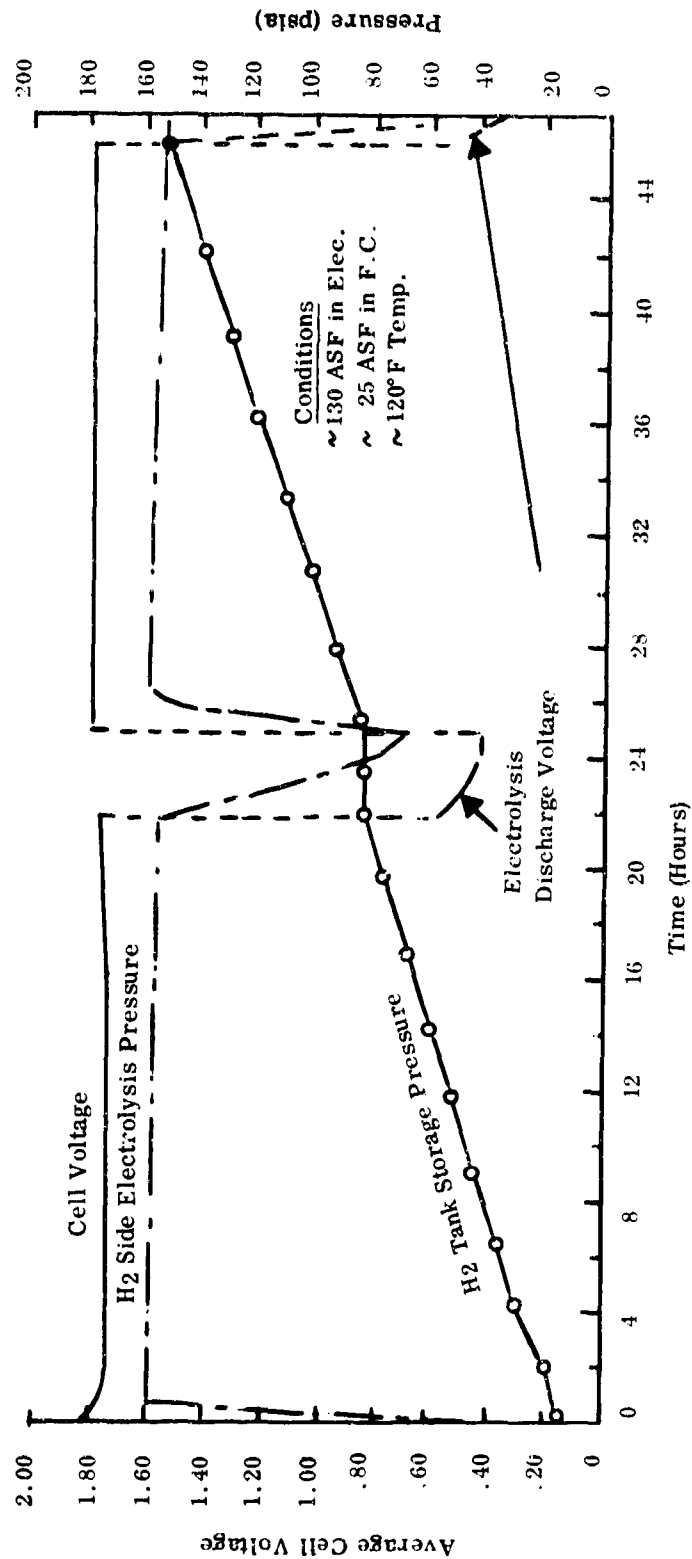


Figure 30. 3-Cell Electrolysis Stack Testing - Component Checkout in Breadboard

Breadboard Regenerative Fuel Cell System Testing

During all of the electrolysis unit testing in the breadboard system, the 6-cell fuel cell stack was maintained on open circuit utilizing an external bottle gas supply and intermittently operated at full load conditions from 17 February to 8 April 1970. The fuel cell unit was connected to the breadboard system gas storage tanks and testing was conducted on the system to establish the system energy efficiency with the fuel cell unit maintained at open circuit condition during the daily standby condition (approximately 23 hours).

Three 72-minute discharge cycles were attempted on the fuel cell stack utilizing a mixture of electrolysis gas and bottle gas, with the subsequent recharge of the gas tanks with the electrolysis unit. The fuel cell stack was unable to sustain full load application for the complete 72 minutes due to the breadboard system gaseous inerts. Approximately one liter of gas was purged through each side of the fuel cell stack after completion of its run with no attempt to recharge with external water. This method will eventually condition the gas to a high purity level due to the replacement with high purity electrolysis gas, providing enough water is left in the system for water electrolysis for the 72-minute run. Indications showed that there was an excess of charge water within the system.

A sample obtained from the gas storage tanks after the first run was analyzed and showed the following mole per cent constituents:

Oxygen Side

H<sub>2</sub> ~.228 mole %  
 H<sub>2</sub>O ~.240 mole %  
 N<sub>2</sub> ~1.012 mole %  
 Ar ~.113 mole %  
 CO<sub>2</sub> ~.160 mole %  
 O<sub>2</sub> ~ balance

Hydrogen Side

H<sub>2</sub>O ~.248 mole %  
 N<sub>2</sub> ~.156 mole %  
 O<sub>2</sub> ~.026 mole %  
 Ar ~.011 mole %  
 H<sub>2</sub> ~ balance

This indicates a purity level of 99.5% on the hydrogen side and 98.25% on the oxygen side, which is close to the purity level of standard bottle gas. Therefore, purging would be required to sustain fuel cell operation. Purging of the stack during fuel cell operation would not affect performance of cells 5 and 6, thus demonstrating a gas flow problem probably on the oxygen side in this module. All other cells would increase in performance from the purge application. Since the fuel cell stack must operate without a purge in the regenerative fuel cell system application, continued fuel cell operation, purging and subsequent electrolysis would improve the gas purity to a level such that full-load performance should be sustained for the full 72-minute cycle.

Figure 31 illustrates the fuel cell operation during three runs in the breadboard regenerative system. Full load was reduced to one-half load if a cell fell below .65 volt during the run and operation was continued on the fuel cell to consume an equivalent amount of gas equal to full load operation for 72 minutes (2520 amp-minutes). The power input and operating time were recorded to the electrolyzer to replenish the gas to the same pressure level prior to the run. Integration of the area under the curves in Figure 31 and multiplying by the associated current (either 35 or 17.5 amps) is a measure of the output energy from the fuel cell. The following results were obtained on the first two runs.

<u>Run No.</u>	<u>Fuel Cell Amp-mins</u>	<u>Input Watt-hrs</u>	<u>Output Watt-hrs</u>	<u>System Eff.</u>
1	2480	552	192.6	34.6%
2	2625	640	201.5	31.5%

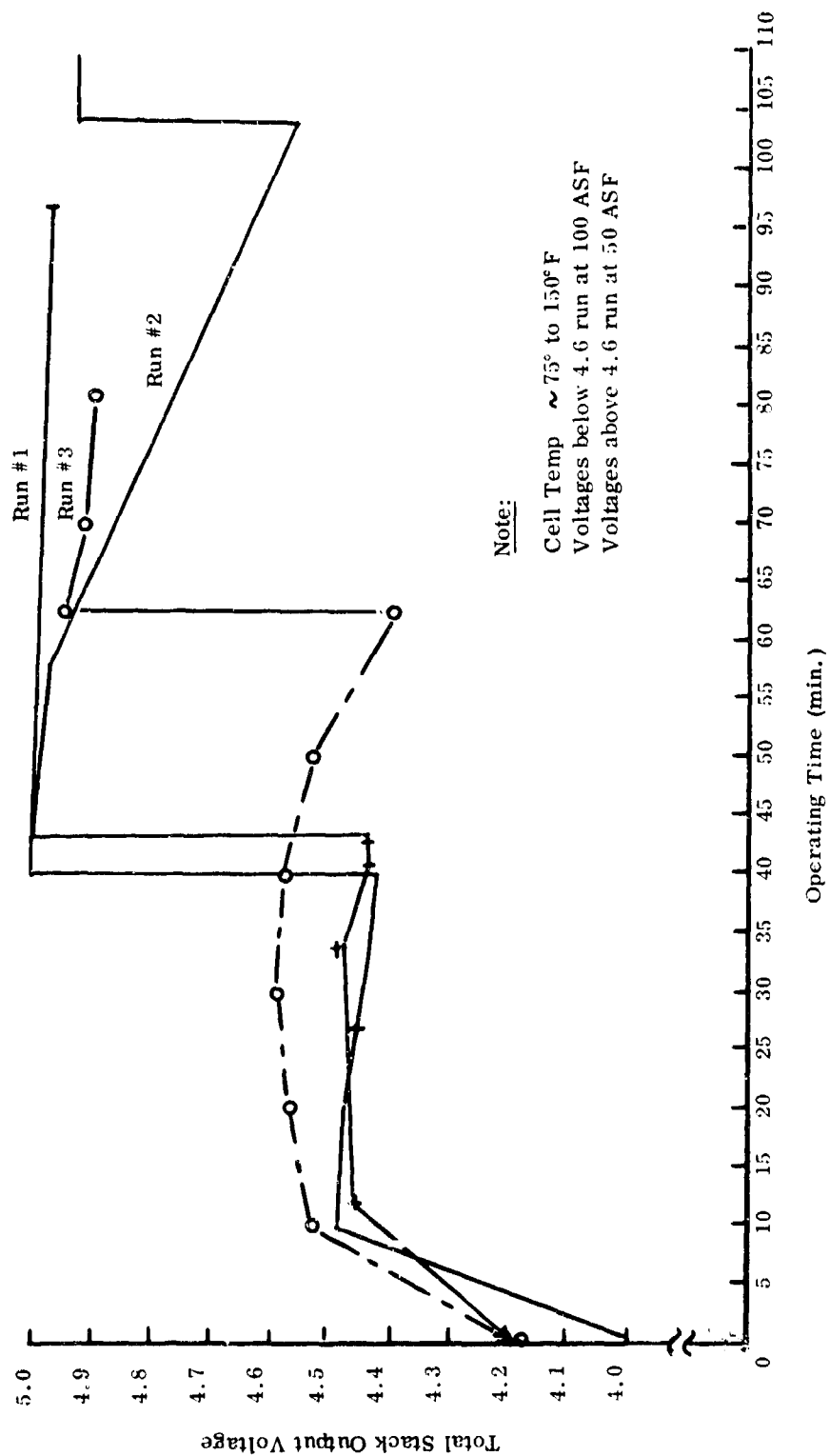
It will be noted from Figure 31 that the third run lasted for 62 minutes at full load before the load had to be reduced due to a low performing cell, thus the system gas purity was improving with each fuel cell and electrolysis cycle. Run No. 3 system energy efficiency is not reported since the electrolysis mode was incomplete.

No attempt was made during these runs to isolate the fuel cell unit from the gas reactant storage tanks, thus the average system energy efficiency of 33% is comparable to the predicted efficiency of 38.4% at this condition. The procedure of fuel cell stack gas storage tank isolation during unit standby was not accomplished in the program since it required further technique development with additional fuel cell hardware which was not available due to emphasis on the breadboard system testing. From an electrochemical analysis, the technique is entirely feasible but would require development of the input power control level and operating time for a particular cell configuration and a number of fuel cell units. The input power control level would depend on valve locations and elimination of potential gas accumulation areas in the free gas space between the cell and the isolation valve. It is anticipated that the demonstrated system energy efficiency will be increased with the elimination of the entrained gaseous inerts from unit startup, resulting in more efficient operation of the fuel cell and correction of several system gas leaks which existed throughout the testing.

Figure 32 illustrates the total accumulated regenerative system testing in the program to the mission daily load profile. During this testing the electrolysis unit successfully operated in the fuel cell mode to "bulk transfer" the fuel cell product water to the electrolysis unit. The average power output of the fuel cell stack was 160 watts during the 12 minute and 16.5 minute cycle. The electrolysis unit failed after the second cycle due to an inadvertent gas pressure reversal across the unit upon completion of the fuel cell mode of operation on the electrolysis unit for product water transfer. Teardown of the unit showed a small pinhole in Cell No. 2 of the stack. It was concluded that the failure was caused by the inability of the round

cross-sectional O-ring to withstand potential reverse gas differentials in the application. A square cross-sectional O-ring configuration was reassembled into the unit with three new cells and all gas/water screens were platinized to reduce electrical contact resistance growth.

After successful completion of the electrolysis unit system checkout, the regenerative system testing was again initiated to reduce the system gaseous inert level by repeated fuel cell operation, subsequent gas purging and refilling the system with distilled water. The 6-cell fuel cell unit failed during this testing sequence when the fuel cell stack was restarted after a three day standby condition immediately after opening the gas storage tank solenoid valves. The cause of the stack failure was operator error in not recognizing that with the fuel cell stack isolated from the gas supply, oxygen diffused to the hydrogen side cavities of the stack. Upon application of hydrogen from the system storage tanks, a failure occurred within the unit. This failure was obviously caused by the mixing of hydrogen with the oxygen which had diffused to the hydrogen side of the cells during the three days of standby. This problem could have easily been avoided if the situation had been recognized by the operator. In the final application, the unit would have the hydrogen side electrochemically cleared of oxygen prior to the opening of the hydrogen solenoid valve after any extended period of standby operation. However, it was felt that an investigation of this technique was beyond the scope of this program.



Note:

Cell Temp ~ 75° to 150° F  
 Voltages below 4.6 run at 100 ASF  
 Voltages above 4.6 run at 50 ASF

Figure 31. Breadboard Regenerative System Fuel Cell Operation

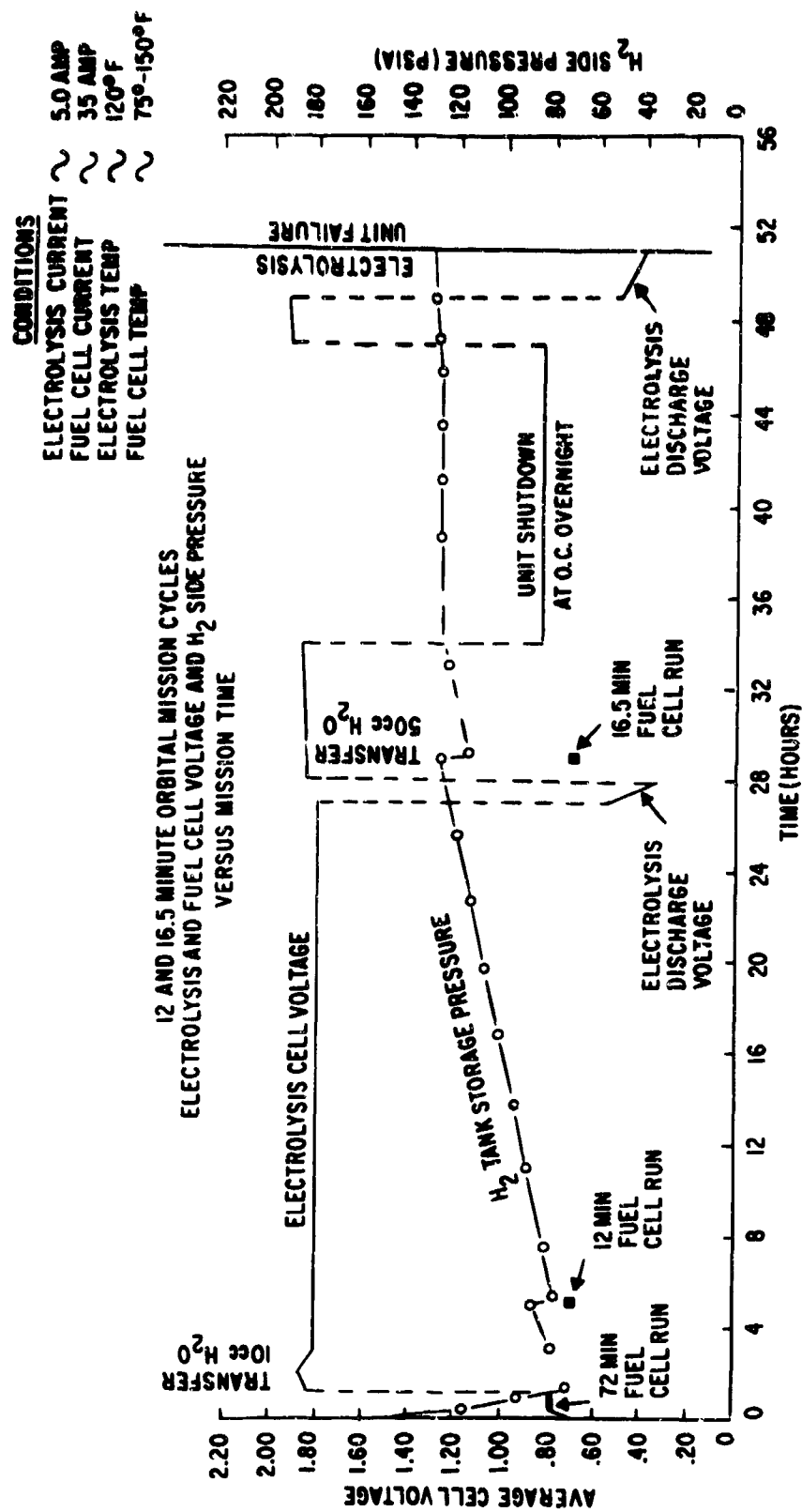


Figure 32. Regenerative Fuel Cell Breadboard System Testing

CONCLUSIONS AND RECOMMENDATIONS

The integrated regenerative fuel cell system concept with the supporting design and test data described in this report is considered to be in the early stages of hardware development. The procedure for increasing the system energy efficiency to the design objective of 45% will require more fuel cell units to demonstrate a reliable startup procedure and thus avoid a failure like that of the 6-cell stack in the regenerative breadboard system. If the regenerative fuel cell system is required to be capable of instant startup during any portion of the 45-day eclipse season, the system operational procedure will have to be modified to maintain the fuel cell stack on open circuit or active gas reactants. This will result in a system energy efficiency of between 33 to 38% as finally determined by the flight weight hardware. Further improvement in the system energy efficiency might be possible with further development by reducing the gas diffusion losses across the two components (fuel cell and electrolysis unit) by means of increasing the thickness of the membrane with some loss in performance.

Further system weight reduction will require extensive hardware development efforts in all components with particular emphasis on the fuel cell unit if energy density is considered a major design objective. Any new system trade-off study conducted should include the weight penalties assessed for particular levels of system energy efficiency and the total effect on the spacecraft with a given solar panel array.

This program has demonstrated the technical feasibility of the system concept and has identified particular component hardware problem areas which can only be solved by continued design and development of the basic hardware concept to obtain reliable components. Laboratory single-cell tests have indicated that the basic membrane and electrode structure is capable of exceeding the life and performance requirements of both the fuel cell and electrolysis unit for this application. The final 8-cell stack life tested in the program exceeded the operating load life for a 5-year mission and the 3-cell electrolysis life is unknown since the final design from this program is still not fully tested.

It is anticipated that with continued system development, both in component design and operational procedural development, that this system concept will offer advantages for regenerative fuel cell system applications requiring 5 - 10 year calendar life.

## APPENDIX I

CONTRACT F33615-69-C-1140

EXHIBIT "A"

DATED: 68 Jun 12

PAGE 1 of 3 PAGES

### STATEMENT OF WORK

#### Regenerative Fuel Cell

1.0 OBJECTIVE: Develop and define the performance and life characteristics of regenerative fuel cell technology for space applications.

2.0 APPROACH: Develop, design, build, and test a functionally complete breadboard regenerative fuel cell.

3.0 APPLICATION: A major potential application for this technology is as part of the electrical power supply for military communications satellites. Although the exploratory nature of this program and the wide range of potential power requirements preclude optimization at this time, preliminary design and test data can be acquired to support future programs. The desired regenerative fuel cell characteristics for military communications satellites are:

#### 3.1 Strategic COMSAT:

Power Level	400 - 1000 watts
Cycle Life	500 cycles
Calender Life	5 - 7 years
Maximum Discharge Time	72 minutes
Energy to Weight Ratio	35 watt-hr/lb
Energy Efficiency	45%

$$\frac{(V_{\text{discharge}})(\text{amp-hr}(\text{out}))}{(V_{\text{charge}})(\text{amp-hr}(\text{in}))}$$

#### 3.2 Tactical COMSAT:

Power Level	1 - 5 kilowatts
Cycle Life	500 cycles
Calender Life	5 years
Maximum Discharge Time	72 minutes
Energy to Weight Ratio	40 watt-hr/lb
Energy Efficiency	45%



4.0 REQUIREMENTS: Contractor shall provide the necessary personnel, facilities, materials, and equipment to develop, design, build, test, and deliver to the Air Force for extended life test, a breadboard regenerative fuel cell power system.

4.1 Representative Mission: For the purposes of this program, Contractor shall assume the following requirements for a full size regenerative fuel cell power system:

Power Level (continuous during discharge)	1000 watts
Cycle Life	450 cycles
Calendar Life (goal)	5 years
Maximum Discharge Time	72 minutes
Energy to Weight Ratio	35 watt-hr/lb
Energy Efficiency	45%
Use Profile	Figure 1
Voltage and Voltage Regulation	28± 10% volts

4.2 Research and Engineering: Contractor shall do such research and engineering as is necessary to fulfill the requirements of this document. This shall include, as necessary, effort on electrolysis, power production, valving and regulation, controls, materials, heat and mass transfer, etc. Contractor shall identify critical problem areas, assess the risk involved, describe preferred and alternate approaches to solutions, and report progress toward those solutions.

4.3 Design: Contractor shall design a breadboard regenerative fuel cell. This breadboard shall:

4.3.1 Be capable of fulfilling all requirements of the representative mission of paragraph 4.1 except for Power Level, Energy to Weight Ratio, and Voltage and Voltage Regulation. For the breadboard:

4.3.1.1 The Power Level shall 150 to 200 watts.

4.3.1.2 The Energy to Weight Ratio is not specified, however, the contractor shall show that the features and performance of the breadboard are consistent with attainment of an Energy to Weight Ratio of 35 watt-hrs/lb in a full size flight type power system.

4.3.1.3 The Voltage and Voltage Regulation shall be a pro-rata portion of the requirements of paragraph 4.1 based on the ratio of breadboard Power Level to the Power Level of paragraph 4.1 (1000 watts).

4.3.2 Be functionally complete for demonstration of the requirements of this document with the exceptions of (1) a suitable source of electricity for regeneration of reactants, and (2) normal laboratory equipment for measuring and recording performance (voltage, temperature, pressure, etc.). All instrumentation leads and transducers shall be provided properly connected to the breadboard and ready for connection to normal laboratory data equipment.

4.3.3 Be of a design that is functionally suitable for scale-up to a full size prototype.

4.3.4 Be of a design that is physically suitable for scale-up to a full size prototype by the addition of components of the same size and functional design as those used in the breadboard; i.e. to the extent possible, the design of the breadboard shall be suitable for scale-up by the addition of "same size" critical components, such as the electro-chemical cells, rather than by resizing such components for greater capacity.

4.4 Design Review: Contractor shall give a detailed final design review at the Air Force Aero Propulsion Laboratory before starting fabrication of the breadboard.

4.5 Fabrication: Contractor shall fabricate the breadboard regenerative fuel cell described in general in paragraph 4.3 and in detail in the Design Review of paragraph 4.4.

4.6 Test: Contractor shall test the breadboard regenerative fuel cell fabricated under paragraph 4.5. The breadboard shall be tested for 45 days to the eclipse period described in Figure 1. The breadboard shall then be delivered to the Air Force Aero Propulsion Laboratory for extended life testing to the eclipse period - dormant period sequence described in Figure 1.

5.0 TECHNICAL PLAN: A technical plan shall be submitted by the contractor to the Procuring Agency. This plan shall define the technical approach which will be followed by the contractor to meet the requirements of this exhibit. This plan shall be an outline in the contractor's proposal and presented in detail as an attachment to first monthly technical status report. As the work progresses, desirable modifications in the technical approach shall be prepared as revisions to the technical plan, and submitted with the appropriate monthly status report. The original plan and revisions, thereof, shall be approved by the Procuring Agency prior to accomplishment of the work described therein. This plan and revision, thereof, shall not alter contract requirements but will define the methods of approach by which contract requirements will be met.

HARDWARE AND SAMPLES

1. Hardware

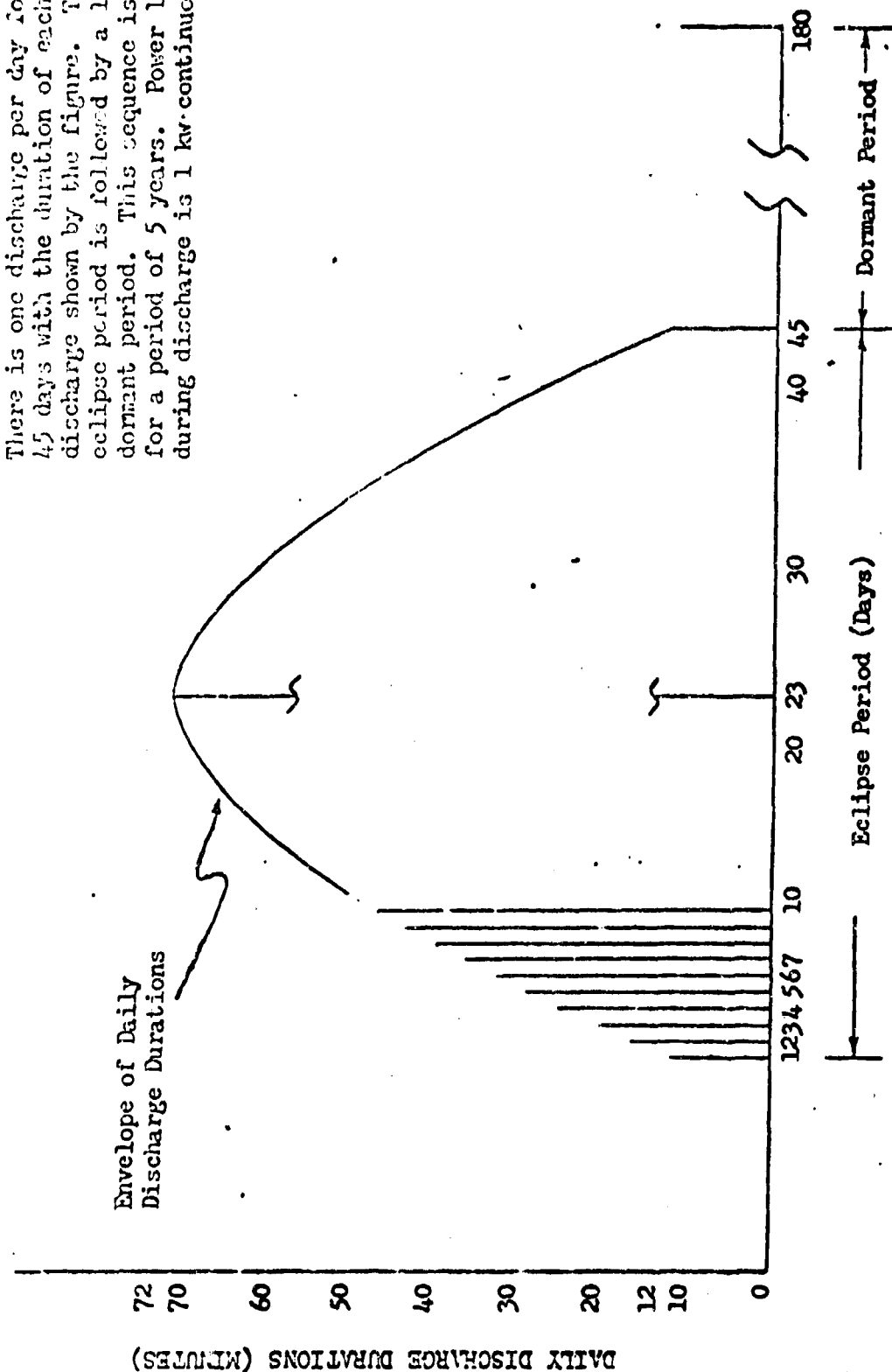
200  $\pm$ 20% watt breadboard regenerative fuel cell shall be fabricated and delivered to AFAPL.

2. Representative Samples

Representative samples will be delivered to AFAPL upon request throughout the life of the contract. These samples may be either operable or inoperable, and will be utilized for demonstration and training at AFAPL. These samples should not be specifically fabricated for this purpose, but shall be items which were fabricated to meet the experimental requirements of the contract and which are no longer needed for the original purpose because of failure, completion of test, design change, etc.

DAILY DISCHARGE DURATIONS

There is one discharge per day for 45 days with the duration of each daily discharge shown by the figure. The eclipse period is followed by a 135 day dormant period. This sequence is repeated for a period of 5 years. Power level during discharge is 1 kw continuous



## APPENDIX II

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CASE 707

### REGENERATIVE FUEL CELL SYSTEM CHARACTERISTICS

#### OVERALL SYSTEM

FUEL CELL POWER	150	WATTS
ACTUAL ENERGY EFFICIENCY	0.3842	
FUEL CELL OPERATING TIME	72	MIN

#### ELECTROLYZER OPERATING TIMES

TOTAL ( 21 HR 58 MIN 4 SEC)	21.968	HR
GAS DELIVERY TO TANKS ( 21 HR 24 MIN 50 SEC)	21.414	HR
CHARGING TO OPERATING PRESS ( 33 MIN 14 SEC)	0.554	HR
EVACUATION FOR FUEL CELL MODE ( 49 MIN 55 SEC)	0.832	HR

#### FUEL CELL(FUEL CELL OPERATING MODE)

STACK OUTPUT VOLTAGE	5.006	VOLTS
STACK CURRENT	29.96	AMP
NUMBER OF CELLS IN SERIES	6	CELLS
CELL ACTIVE AREA	51.66	SQ IN.
CELL CURRENT DENSITY	83.5	AMP/SQ FT
SPE THICKNESS(WATER CONTENT= 0.278917 CC/CC SPE)	0.01	IN.
FUEL CELL VOLTAGE	0.834	VOLTS
FUEL CELL AMP-HOURS	215.7	AMP-HRS
EQUIVALENT FUEL CELL AMP-HOURS	261.4	AMP-HRS
CELL OPERATING TEMP	150	DEG F
OXYGEN PRESSURE	52.3	PSIA
HYDROGEN PRESSURE	51.7	PSIA
PRODUCT WATER OUTLET PRESSURE	50	PSIA
FUEL CELL FARADAIC EFFICIENCY	0.981	
EQUIV CURRENT(PERMEABILITY LOSS)	0.582	AMP
EQUIV CURRENT DENSITY(PERM LOSS)	1.621	AMP/SQ FT
EQUIV CURRENT DEN(PERM LOSS/ELECTROLYSIS MODE)	0.846	AMP/SQ FT

#### ELECTROLYZER (FUEL CELL MODE)

OXYGEN SIDE PRESSURE(START OF F/C MODE)	11.615	PSIA
OXYGEN SIDE PRESSURE(END OF F/C MODE)	25	PSIA

#### REACTANT STORAGE

##### HYDROGEN TANK

INTERNAL VOLUME( 1090.4 CU IN.)	0.631	CU FT
INTERNAL DIAMETER(SPHERE TANK)	12.77	IN.
PRESSURE(MAX)	166	PSIA
PRESSURE(MIN)	60	PSIA

##### OXYGEN TANK

INTERNAL VOLUME( 545.2 CU IN.)	0.316	CU FT
INTERNAL DIAMETER(SPHERE TANK)	10.14	IN.
PRESSURE(MAX)	166	PSIA
PRESURE(MIN)	60	PSIA

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CASE 707

## SYSTEM WATER BALANCE

WATER IN ELECTROLYZER(TOT AT START= 5.65 CU IN.)	0.202	LB
WATER ELECTROLYZED ( 5.42 CU IN.)	0.194	LB
WATER TO CHARGE ELECTROLYZER( 0.14 CU IN.)	0.005	LB
WATER LOSS TO HYDROGEN TANK	0.002	LB
WATER LOSS TO OXYGEN TANK	0.001	LB
WATER LOSS TO REACTANT TANKS( 0.084 CU IN.)	0.003	LB
WATER TO SAT RESIDUAL GAS(H2 TANK)	0.0031	LB
WATER TO SAT RESIDUAL GAS(O2 TANK)	0.0016	LB
TOT WATER IN ELECTROLYZER & STORAGE TANKS(START)	0.206	LB

## ELECTROLYZER (ELECTROLYSIS MODE)

STACK VOLTAGE	5.08	VOLTS
CELL CURRENT	4.199	AMP
NUMBER OF CELLS IN SERIES	3	CELLS
CELL ACTIVE AREA	5.53	SQ IN.
CELL CURRENT DENSITY	109.3	AMP/SQ FT
SPE THICKNESS(WATER CONTENT= 0.278917 CC/CC SPE)	0.01	IN.
ELECTROLYZER CELL VOLTAGE	1.693	VOLTS
ELECTROLYSIS CELL CHARACTERISTIC VOLTAGE	1.642	VOLTS
VOLTAGE CORRECTION FOR SAT ANODE OPERATION	0.0233	VOLTS
VOLTAGE CORRECTION FOR PRESSURIZED OPERATION	0.0273	VOLTS
CELL OPERATING TEMP	120	DEG F
ELECTROLYZER FARADAIC EFFICIENCY	0.969	
EQUIV CURRENT(PERMEABILITY LOSS)	0.13	AMP
EQUIV CURRENT DENSITY(PERM LOSS)	3.38	AMP/SQ FT
HYDROGEN SIDE VAPOR PRESSURE	1.693	PSIA
OXYGEN SIDE VAPOR PRESSURE	1.49	PSIA
HYDROGEN DELIVERY PRESS	166	PSIA
OXYGEN DELIVERY PRESS	166	PSIA
HYDROGEN SIDE VOLUME	18.49	CU IN.
OXYGEN SIDE VOLUME	9.84	CU IN.
OXYGEN SIDE VOID VOL(START)	4.19	CU IN.

## CASE 707

ELECTROLYZER CELL OPERATING CHARACTERISTICS  
ELECTROLYZER CELL AC IMPEDANCES AT 75 DEG F

MEMBRANE AC IMPEDANCE	11.635 MILLIOHMS
MEM/ELECTRODE COLLECTION AC IMPED	13.462 MILLIOHMS
ELECTRODE RESISTIVITY SUM(R2+R3)	12.34 MILLIOHMS
CURRENT COLLECTION LENGTH	1.592 INCHES
CELL CONTACT RESISTANCE LOSSES	8.087 MILLIOHMS
CELL ASSY AC IMPEDANCE	21.549 MILLIOHMS

## ELECTROLYZER CELL AC IMPEDANCES AT 120 DEG F

MEMBRANE OPERATING AC IMPEDANCE	10.37 MILLIOHMS
MEMBRANE OPEN CIRCUIT AC IMPEDANCE	8.758 MILLIOHMS
CELL ASSEMBLY OPERATING AC IMPEDANCE	18.654 MILLIOHMS
CELL ASSY OPEN CIRCUIT AC IMPED	18.457 MILLIOHMS

## ELECTROLYZER CELL DC IMPEDANCES AT 120 DEG F

IR FREE DC CELL IMPEDANCE	2.895 MILLIOHMS
MEMBRANE DC IMPEDANCE	13.265 MILLIOHMS
MEMBRANE/ELECTRODE COLLECTION DC IMPED	15.098 MILLIOHMS
CELL ASSEMBLY DC IMPEDANCE	23.186 MILLIOHMS

## ELECTROLYZER CELL CURRENT DENSITY VARIATIONS

MAXIMUM CURRENT DENSITY	124.5	AMP/SQ FT
AVERAGE CURRENT DENSITY	109.3	AMP/SQ FT
MINIMUM CURRENT DENSITY	101.9	AMP/SQ FT

## ELECTROLYZER CELL VOLTAGE ANALYSIS SUMMARY

CELL ASSEMBLY VOLTAGE	1.693 VOLTS
MEMBRANE/ELECTRODE ASSY TERM VOLTAGE	1.659 VOLTS
CONTACT RESISTANCE LOSSES	0.034 VOLTS
IR FREE VOLTAGE AT AVE CURRENT DENSITY	1.608 VOLTS
VOLTAGE CORRECTION FOR SAT CATH OPERATION	0.0233 VOLTS
VOLTAGE CORRECTION FOR PRESSURIZED OPERATION	0.0273 VOLTS
NERNST CORRECTION CORRELATION FACTOR	0.5

## MEMBRANE WATER CONTENT DISTRIBUTION

LOCATION	GM/GM DRY WT	CC WATER/CC TOT VOL
CATHODE	0.191	0.279
1	0.174	0.26
2	0.158	0.242
3	0.143	0.224
4	0.13	0.208
ANODE	0.118	0.192

Appendix III  
Operating Instructions for  
150-200 Watt Breadboard Regenerative  
Fuel Cell System

1.0      Introduction

The Regenerative Fuel Cell Breadboard System is designed to permit operation of the gas generation subsystem and the fuel cell unit independently of each other or as a combined unit. Operation of the electrolysis cycle is automatic and may be run unattended for extended periods. However, operation of the fuel cell and the transfer of water to the electrolyzer require manual operation with 1 - 3 hours of attended operation daily depending upon the length of fuel cell operation. For safe, unattended operation the system should be provided with three automatic safeguards as follows:

- 1) A high-voltage trip to remove power from the electrolyzer if the electrolyzer cell voltage rises too high. This might occur if the unit ran low on water.
- 2) A low-voltage trip to shut off the hydrogen and oxygen supply and substitute nitrogen in the event of a severe drop in the fuel cell stack voltage.
- 3) A low-pressure trip to supply gas to the gas storage tanks from an external facility supply in the event the fuel cell unit case pressure drops below 50 psig.

Figure 20 and Table II illustrate a fluid flow schematic in the test setup incorporating these devices in addition to all other system components.

Since external pressure instrumentation and connecting lines essentially become part of the working volume of the breadboard system, it is essential that their volume be kept at a minimum and be arranged so that condensed water vapor will drain back into the system.

2.0      System Preparation

The procedure for cleaning the gas system of air and other impurities is to first evacuate all of the system except the fuel cell and its test case and subsequently refill the system with electrolyzed gas. The fuel cell becomes a storage volume for all system impurities. These impurities can be externally purged and makeup water added to equal the purged gas. This procedure will require several cycles of regenerative operation to achieve the required level of gas purity. All instrumentation



and connecting lines should be thoroughly purged with the desired gas (hydrogen or oxygen) before connection to the unit.

Water added to the system for startup and to make up for losses due to purging should be distilled water that is boiled to reduce the amount of dissolved gases. During the boiling process, oxygen should be bubbled through the water to further reduce the quantity of impure gas dissolved in the water. The water should be transferred to an evacuated pressure vessel while hot, and after cooling to room temperature transferred to the system deionizer through Port V26 (Figure 20) by pressurizing the water pressure vessel with oxygen. Fill only to the top of the deionizer and vent the gas as required through Valve V27, otherwise excess water will rise up into fuel cell test case. Do not permit the water level to drop below the minimum mark on the deionizer as this will permit the pressurizing oxygen to enter the electrolyzer and reduce the system purity.

To evacuate the system, Valves V1 and V4 must be closed with the fuel cell stack maintained on an external bottle gas supply or operating at open circuit condition on the gas trapped in the test case. Vent the gas pressure in the system out of V30, V31 and V32 and attach a vacuum pump to these ports. Use a water trap on the vacuum line to prevent pump oil vapor from entering the system. H<sub>2</sub>O Solenoid SV4 should be closed during the evacuation process. This evacuation clears both sides of electrolyzer and the associated gas storage system up to the fuel cell.

To transfer water from the deionizer bed to the electrolyzer, open Solenoid Valve SV4 and then Valve V25. In order for water to transfer, the electrolyzer oxygen pressure must be less than the deionizer back-pressure (set at 30 psig) through Port 10. The approximate water capacity of the oxygen side of the electrolyzer is 150 cc.

### 3.0 Electrolysis Unit Operation

To operate the electrolyzer, apply DC power with proper polarity to the electrolyzer that has previously been provided with the required amount of water (5.09 cc/hour of electrolyzer operation). Initial operation should be at 1.0 amp for the first 5 minutes. Subsequent maximum current input should never exceed 5 amps. Each cell voltage should be uniform and within 1.3 to 1.8 volts, depending upon input conditions and unit temperature. High voltage on any cell indicates dryness or cell damage, low voltages indicate electrical shorts. Either condition should be corrected before continued operation. With the unit operating at 5 amps input, the electrolyzer pressure will rise rapidly. Ensure that Valve V24 is open and Water Transfer Valve V25 and Solenoid Valve SV4 are closed.

Control of the electrolyzer pressure is by means of the Absolute Pressure Relief Valves OR2 and HR2. These valves are set for 165 psia, however some adjustment may be required during initial startup and a very slight movement

(clockwise to increase) of the nut at the top of the valve should produce the desired pressure level. During operation, the pressure settings may change  $\pm 15\%$  as the pressure increases in the storage tanks. These pressure fluctuations may also cause variations in electrolyzer performance but are not harmful to the unit. Best performance is obtained by adjusting the  $H_2$  pressure to be 10 psi higher than the  $O_2$  pressure. The electrolyzer input power passes through two pressure switches which are wired to open when either storage tank pressure reaches 145 psia.

As the system is presently wired, Switch W1 must be manually moved to the open circuit condition or with further movement to the fuel cell position prior to reducing tank pressure. This prevents reapplication of electrolyzer power when the tank pressure drops by 15 - 20 psig.

If the electrolyzer is operating at 5 amps in a 75°F ambient, it will achieve a stable temperature of 90 - 100°F and no additional heat will be required. If higher operating temperatures are desired, apply power to the heating tape through a Variac and adjust the level for the desired temperature. Do not exceed 160°F unit operating temperature. Unit temperature may be read from the thermocouples connected to a Copper-Constantan bridge.

To set the high voltage shutdown, use a voltage of 0.1 volt/cell higher than the operating voltage after the unit pressure and temperature have stabilized at the start of the electrolysis cycle. Careful control of water volumes in the electrolyzer is necessary during the water filling operation to prevent drying of the electrolyzer cells. Rapid rise in cell voltage is indicative of a drying condition.

Fuel cell operation of the electrolyzer is conducted to reduce the oxygen pressure sufficiently to permit water transfer to the electrolyzer. To operate the unit as a fuel cell, turn Switch W1 to the fuel cell position. The resistor should be set to pass 2.0 amps at nominal operating pressure and temperature at the start of fuel cell operation. Allow the switch to remain at this setting to permit the current to decline as gas is consumed. At the conclusion of the fuel cell operation of the electrolysis unit, the oxygen pressure should be 0 - 2 psia and the necessary quantity of water may be transferred from the deionizer tank or accumulator to the  $O_2$  side of the electrolyzer.

#### 4.0 Fuel Cell Unit Operation

To activate the fuel cell stack on bottled gas first ensure that Valves V1 thru V12 and V19 and V23 are closed so that the fuel cell is isolated from the external hydrogen and oxygen or internal system and the gas supply. Purge both sides of the unit with nitrogen to remove any active gases. This is accomplished by connecting a nitrogen line at 0 psig to the Coolant Pressurization Port 4 and to the  $O_2$  and  $H_2$  sides through V2 and SV3 by means of Valve V12 to permit removal of  $N_2$

from the H<sub>2</sub> side. SN3 should be de-energized and not connected through PS1 during this operation. A line is connected to the deionizer at Port 10. Open Valves V2, V5, V6, V7, V11 and V12. Increase the fuel cell case pressure to 3.0 psig. Adjust other pressures to achieve O<sub>2</sub>-to-H<sub>2</sub> equal to 0 → 10 inches H<sub>2</sub>O and O<sub>2</sub>-to-coolant equal to 0 → 10 inches H<sub>2</sub>O. Check for gas leaks in the system. Purge 3 liters of nitrogen through Valve V3 at 1 liter/min. rate. Purge the test case with 100 liters nitrogen at 4 liters/min. through Valves V7 and V9, with V6 closed. Set a constant purge of the O<sub>2</sub> side of the stack through Valves V8 and V6 at 10 - 20 cc/min. bleed rate.

With all sides purged, close Valves V2 and V12 and remove the nitrogen line and connect a purged H<sub>2</sub> line to V2. Slowly open V2 and adjust the hydrogen pressure for 30 inches H<sub>2</sub>O O<sub>2</sub>-to-H<sub>2</sub> ΔP.

Purge 3 liters of hydrogen through the hydrogen side by slightly opening Valve V3. Set a constant H<sub>2</sub> purge rate of 10 - 20 cc/min. The cell voltages should rise to 0.95 to 1.05 volts per cell. Apply a 5 amp load and discharge cells to .05 ± .02 volts/cell. With no load, all cells should not rise above 0.15 volt within one minute. If the voltage rise is above this rate, reapply the load and repeat until satisfactory. Stop the purge process by closing V8 and V3. Also close V5, V11 and V12 and remove V12 and cap Port B of SN3. Connect a purged O<sub>2</sub> line to Port C of SN3 and adjust the pressure to 3.5 psig and open V5, admitting oxygen to the stack. Set the gas pressures at: O<sub>2</sub>-to-H<sub>2</sub> of 30 ± 10 inches H<sub>2</sub>O; O<sub>2</sub>-to-coolant of 10 ± 10 inches H<sub>2</sub>O; and O<sub>2</sub>-to H<sub>2</sub>O of 60 ± 10 inches H<sub>2</sub>O.

Slowly raise the test case pressure to 5.0 psig while maintaining the respective differential pressures. Purge the case with 100 liters of oxygen at 4 liters/min. by opening V9. At the same time, purge the O<sub>2</sub> side of the stack at 4 liters/min. until all cells read a minimum of 1 volt, then close Valve V8. At completion of the 100 liter volume purge of the case, close Valve V9 and purge the fuel cell stack for an additional 3 liters through Valve V8.

Set the automatic low voltage trip to apply nitrogen at a 4.0 volt setting. Open circuit performance at this point should be normal.

To obtain an operating test case pressure of 38 psig, it is necessary to increase the spring load on the test case end plates to maintain the case seal against the gasket and at the same time to vent at 38.5 to 40.0 psig for safety. To raise the case pressure, first tighten the case tie bolt nuts one turn at a time in a 12-6-3-9-11-5-2-8 o'clock sequence until four turns are achieved. Increase the pressure to 15 psig while maintaining the differential pressures. Repeat the process until an oxygen case pressure of 38 psi is achieved. Check for leaks at this level and for case venting at the 38.5 - 40 psig pressure level. Adjust the bolt tension to achieve proper leak-vent-pressure relationship. The purpose of the progressive tightening procedure is to prevent cutting of the case gaskets due to the high spring loading. The same procedure should be reversed when lowering the unit case pressure. One turn on the tie bolt arrangement is equivalent to 3.5 psig.

Fill the coolant system through V19 with distilled water. Adjust the coolant flow at V22 and V23 to maximum flow while maintaining the proper differential pressure. Set a 5 amp load on the unit. All cells should be above 0.9 volt. Slowly open Water Valve V10 adjusting O<sub>2</sub> pressure to the deionizer to maintain 60 ± 10 inches H<sub>2</sub>O O<sub>2</sub>-to-H<sub>2</sub>O differential pressure.

Purge the hydrogen side of the stack at 6 liters/min. for 15 seconds through V3. Purge oxygen at 3 liters/min. rate for 15 seconds through V8, then set 17.5 amp (50 ASF load). All cells should be above 0.825 volt. Hold for 30 minutes at this level. Purge both gas sides at the indicated purge rates for 15 seconds and then set 35 amps (100 ASF) or full load. All cells should be above 0.70 volt. Hold 35 amps for 30 minutes and return to unit open circuit condition.

The fuel cell is now activated and has demonstrated adequate performance for system operation, however, considerable running and purging will be required to clean up the large O<sub>2</sub> volume to the degree required for no-purge operation as in the regenerative system. The criterion for purging is if any cell falls below 0.70 volt at 100 ASF.

The fuel cell test case is equipped with resistance-type heaters in addition to the cooling system and both components are equipped with thermocouples to read the coolant in and out temperatures and the test case temperatures. Power to the heaters is controlled by rheostats that are set to hold the coolant inlet temperature at 150°F and the skin temperature 2 - 4°F higher at 100 ASF. These heaters are manually switched on at the time of the fuel cell load application and then switched off for open circuit operation. During the warmup period, there will be expansion of the coolant in the storage tanks and if the nitrogen supply used to pressurize the coolant system is not equipped with a relief regulator it will be necessary to vent some pressure through V19. Prolonged operation of the fuel cell without operating the electrolyzer will cause a buildup of water in the deionizer. Excess water may be removed through V26. Water accumulation rate is approximately 1.5 cc/min. at 100 ASF.

Operation of the fuel cell on electrolyzed gas is similar to that on bottled gas. To connect the fuel to the electrolysis subsystem, adjust the gas unit regulators to maintain the proper fuel cell gas pressures while shutting off the external gas supplies and opening Valves V1 and V4. This supplies the reactant gases from the system gas storage tanks. Ensure that the storage tank pressure is adequate to supply enough gas for the required operating period. Normal gas consumption at 100 ASF is less than 1 psig/min.

After the gas changeover has been completed, Solenoid Valves SV1 and SV2 are connected and energized at the low fuel cell voltage setting (4.0 volts) to shut off the gas supply. In addition, SV3 should be re-piped by connecting the gas line from

the bottled O<sub>2</sub> from Port C to Port B and capping Port C and applying 110 volts to Pressure Switch 1. This change permits external bottle gas to fill the oxygen storage tank if the tank pressure drops below 50 psi. This precaution prevents a high differential gas pressure in the wrong direction in case there is a loss of oxygen.

#### 5.0 Regenerative System Operation

To operate the system on a normal daily mission cycle after the fuel cell unit has been connected to the electrolyzed gas system, begin with the following conditions at the start of the cycle:

- 1) Gas storage tanks at 132 psig
- 2) Fuel cell unit at open circuit with cell voltages above .9 volt
- 3) The electrolyzer unit having a vacuum (5 - 10 psia) on the oxygen side

Switch on the fuel cell heaters and then apply a 35 amp load to the fuel cell, while monitoring all pressures and voltages. Do not permit any cell to drop below 0.60 volt.

At the conclusion of fuel cell unit operation, remove the load and switch off the heaters. Transfer the required amount of water to fill the oxygen side of the electrolyzer (approximately 110 cc if the electrolyzer is empty). Switch on the electrolyzer and set 5.0 amps input current. Monitor the pressures generated during the startup until stable delivery pressure is obtained (usually less than one hour). Set the high-voltage shutdown as previously described. The unit may now be left unattended, however, recording of cell voltages and current would be required to determine the system energy efficiency. When the tank pressures reach the proper charged level, the electrolysis power will be removed automatically. Prior to the next fuel cell operation, switch the electrolysis power through W1 to the fuel cell operation position to evacuate the oxygen side. This completes the daily mission cycle.

The operator is cautioned to maintain proper gas pressure differentials during all fuel cell operations to protect the unit.

In the event of fuel cell shutdown due to low voltage, do not attempt to restart the fuel cell without thoroughly purging the oxygen side with nitrogen and leak-checking the system for oxygen or hydrogen leaks. Such a shutdown will cause oxygen to accumulate on the hydrogen side by diffusion and an accidental reset of the gas tank shutoff solenoids would result in hydrogen entering the oxygen-filled cavities on the fuel cell stack hydrogen side.

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13. ABSTRACT <p>The objective of this Contract was to develop and define the performance and life characteristics of regenerative fuel cell technology for space applications. This report describes the system, analyses, component configurations, test results and conclusions derived from this work effort for this initial developmental program phase. Laboratory-type evaluation electrolysis single-cells (3 x 3 inch size) were fabricated and operated on performance and life tests to determine the design parameters in unit design. Full-size fuel cell units were assembled and tested, with the final 8-cell stack completing 975 hours of testing at the design current density (100 ASF) and 180°F cell temperature. An electrolysis stack configuration was designed and several single and 3-cell stacks were performance tested to develop the design concept. A complete 150 - 200 watt breadboard regenerative fuel cell system was designed and fabricated. The system was performance tested to demonstrate the system energy efficiency (approximately 33%), which compared favorably with a predicted energy efficiency of 38%. Two daily mission cycles (12 minutes and 16.5 minutes fuel cell discharge durations) were completed in the regenerative system prior to an electrolysis unit failure. This testing demonstrated the technical feasibility of an integrated regenerative system approach. Additional hardware development is required to demonstrate system reliability and successful completion of a 45 day eclipse season mission test.</p>		

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